On-line software for the estimation of fetal radiation dose to patients and staff in diagnostic radiology

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Abstract. In this paper we describe an online software, called "Dose Fetal Web", which calculates the dose to the fetus from both medical and occupational exposures of the pregnant woman. It also calculates the risks of in uterus exposure. The software uses the methodology suggest by Osei et al. where coefficients for converting uterus to fetal dose have been calculated by using Monte Carlo simulation. These coefficients are called Normalized Uterine Dose (NUD) and may be used depending on the pregnant's classification. In the case of fetal dose from diagnostic medical examination of the pregnant patient, database information regarding output and other equipment related parameters from the QA database, maternal and fetal parameters collected by ultrasound procedures were used for the fetal dose estimation. In the case of fetal dose from occupational exposure of the pregnant worker the database information regarding routine individual monitoring dosimetry like occupational dose and workload were used for the fetal dose estimation. For example, supposed a 26 weeks pregnant patient had to undergo a single AP Abdomen procedure (70 kVp peak tube voltage and total filtration 3 mmAl), the fetal dose calculated by the "Dose Fetal Web" was 4.61 mGy. The risks calculated by the online program were 5.0×10^{-4} and 0.14 to the probability of mental retardation induction and decline in IQ score, respectively. As a hypothetical example for the occupational exposure, considering that the staff member can be pregnant, and assuming that she wore a 0.5 mm lead equivalent apron during every procedure and a personal dosimetry read of 2 mGy_{TLD}/month measured with the TLDs outside the apron, the fetal dose from occupational exposure in interventional radiology procedure, calculated by the online software, was 0.02 mSv/month.

KEYWORDS: fetal radiation dose; prenatal exposure; pregnant patient; radiological risks.

1. Introduction

The protection of the unborn children of pregnant women from ionizing radiations is very important because the fetus is particularly vulnerable to the effects of ionizing radiation [1-2]. It is therefore important to be able to determine the absorbed dose to the fetus in diagnostic radiology for pregnant patients as well as the fetal dose from occupational exposure of the pregnant worker [3-5].

When a woman were unaware of their pregnancy at the time of her radiological examination or when a pregnant patient must undergo a radiographic procedure, special procedures should be apply with the objective of prevent or minimising fetal dose [4]. These special procedures include information posters on the wall of the radiological department to capture the attention of a woman of reproductive age to advise her to announce the possibility of her pregnancy before the x-ray examination and the restriction of high dose procedures to the first 10 days of the menstrual cycle when conception is unlikely to have occurred [6-8].

The determination of the equivalent dose to the unborn child in diagnostic radiology is of interest as a basis for risk estimates from occupational exposures of the pregnant worker. Routine individual monitoring is necessary to ensure that occupational exposures are being kept as low as reasonably achievable (ALARA) and also that authorized limits are not exceeded [8]. Radiation doses to occupationally exposed staff working with radiological equipments are generally low and it is unlikely that the equivalent dose limit recommended by the National Commission of Nuclear Energy (CNEN) [9] and adopted in the Publication 453 of National Health Surveillance Agency [8] (ANVISA) will be

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exceeded. However, for some fluoroscopy procedures there is a potential for higher radiation doses to staff.

The objectives of the present work are to describe the online program, named “Dose Fetal Web”, developed to evaluate the fetal dose from medical and occupational exposure in radiology procedures and to show some examples considering that the patient or the staff member can be pregnant [10].

2. Methodology

The program presented in this work, named “Dose Fetal Web”, was developed using open source tools like PHP scripts language and a relational database PostgreSQL. The mathematical model, suggest by Osei et al. [2], was incorporated into the web pages to calculate the fetal dose and the radiological risks from pre-natal exposures.

According to the mathematical methodology, the fetal dose was estimated by the using of conversion factors, called Normalized Uterine Dose (NUD), generated from Monte Carlo simulation (ESG4) by Osei et al. [3]. In the case of medical exposure of a pregnant woman, tables of NUD, stored in the database, are presented as the absorbed dose to the uterus relative to the Entrance Surface Dose (ESD) (i.e. mGy_{tis}/mGy_{air}) [3-4]. For occupational exposure of the pregnant worker, tables of NUD also stored in the database, are presented as the ratio of the equivalent dose to the uterus to TLD dosimeter reading (i.e. mSv/mGy_{TLD}) [3,5].

Some other factors affecting the fetal dose and are required by the program, like

(a) the maximal AP thickness of the patient (cm): if this measured is not supplied it can be approximated by the equivalent cylindrical diameter of the patient. This is estimated from the weight (in kg) and height (in m) of the patient assuming that the body is a cylinder with a density of 1.0 g cm^{-3} [11];

(b) the depth of the fetus (cm): this is an important quantity in fetal dose calculations because of the appropriate NUD. The fetal depth in the maternal abdomen should be determined from ultrasound scan. However, if this measured is not supplied, but the AP thickness of the patient is known, the depth is approximated to be about 30% of the AP thickness of the patient [12-13];

(c) the gestational age of the fetus (GA) (weeks): is required by the program in order to choose the appropriate uterus-to-fetus dose conversion factor (SF) and in the risk calculations. The GA should be determined using menstrual history, physical examination or ultrasound scan. It is an important quantity as the risk to the fetus is dependent on the GA [14-17].

2.1 Fetal Dose from Medical Exposure

The fetal absorbed dose from a series of radiographic examinations, D_f , as a function of ESD, for each radiograph is calculated from

$$D_f = \sum_{i=1}^{n} NUD_{d,ESD,i} \cdot ESD_i \cdot SF_i \qquad (1)$$

where n is the number of radiographs, $NUD_{d,ESD}$ is the uterus dose at a mean fetal depth d normalised to the ESD, and SF is the fetal size factor (i.e. uterus-to-fetus dose conversion factor) for the field size used in the examination [3-4].

The entrance surface dose (ESD) for screen-film (or digital) examinations is calculated from

$$ESD = \left(\frac{FSD_{QA}}{FSD_{EX}} \right)^2 \cdot \left(\frac{kVp_{EX}}{kVp_{QA}} \right)^2 \cdot \eta \cdot mAs \quad (2)$$

where FSD is the focus-to-skin distance, kVp is the peak tube potential, η is the tube output rate in mGy.(mAs)$^{-1}$ and mAs is the current-exposure time product used in the examination to deliver the exposure [2]. The subscripts QA and EX denote the parameters used during quality assurance measurements and for the patient examination(s) respectively.

2.2 Fetal Dose from Occupational Exposure

The fetal equivalent dose, F_{eq}, may be calculated from

$$F_{eq} = \overline{NUD_{occ}} \cdot \overline{L_m} \quad (3)$$

where $\overline{NUD_{oc}}$ is the occupational normalized uterine dose, and $\overline{L_m}$ is the average whole body dose by staff [2-3,5].

2.3 Prenatal Radiation Risks

For purposes of estimating the risks following *in utero* exposure, a linear dose relationship with no-threshold concept is assumed [14]. The risk is calculated from

$$p_R = R_e \cdot D_f \quad (4)$$

where p_R is the risk associated with the dose D_f, and R_e is the risk coefficient. Risks coefficients published in the literature [14-18] are shown in the Table 1.

Table 1: Risks coefficients published in the literature [14-18] for some deleterious effect of ionizing radiation, with some explanations.

Deleterious Effect	R_e (mSv^{-1})	Explanations
Decline in IQ score	2.90 x 10^{-2}	Assumed for all GA
Severe mental retardation	4.30 x 10^{-4}	During the 0-15 week, after this period is taken to be 4 times less
Hereditary effects	0.20 x 10^{-5}(a) 0.10 x 10^{-5}(b)	Assumed for all GA
Fatal childhood cancer	5.50 x 10^{-5}(a) 4.10 x 10^{-5}(b)	
Fatal leukemia	1.25 x 10^{-5}	

(a) assumed to the whole exposed population
(b) assumed to the adult workers exposed population

2.4 Online System

The "Dose Fetal Web", Fig. 1, is an online system developed for the estimation of the radiation dose to the fetus [10]. It calculates the absorbed dose and the radiation risks to the fetus from conventional radiographic procedures performed on the pregnant patient and the equivalent dose to the fetus from

occupational exposure of the pregnant worker in the radiology department. When logging into “Dose Fetal Web”, a user is given two menus of case study:

(1) medical exposure of the pregnant patient and
(2) occupational exposure of the pregnant worker.

Figure 1: “Dose Fetal Web” main menu with the two type of case study: “Medical Exposure” of the pregnant patient and “Occupational Exposure” of the pregnant worker

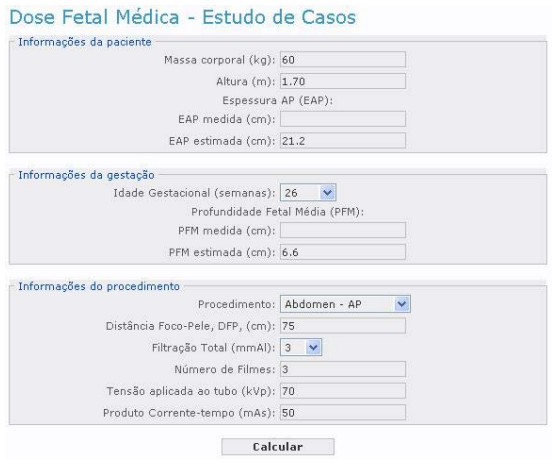
If option 1 is selected, Fig. 2, medical exposure, the user has to provide information about the patient

(a) the height (in m), the weight (in kg) and the antero-posterior thickness (in cm),
(b) the gestational age (in weeks), and
(c) the fetal depth in cm.

The user has also to provide the technique factors used for the examination(s)

(a) the procedure and projection (Abdomen AP, Chest PA or LAT, and Lumbar Spine AP, JLS or LAT),
(b) the focus-to-skin distance (in cm),
(c) the total filtration (in mmAl),
(d) the number of exposures,
(e) the peak tube voltage (in kVp), and
(f) the tube current and exposure time (in mAs).

Figure 2: Electronic form to the case study of the medical exposure of the pregnant patient

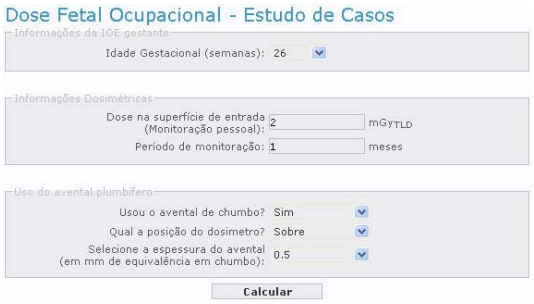


The program uses the data provided by the user and the correspondent NUD to calculate the fetal dose. The result of the fetal dose is presented in a web page with the radiological risks associated with the prenatal exposure. A table with some threshold fetal doses for some deterministic effects following *in utero* exposure like dead, gross malformation, growth and mental retardation, published in the literature, is also presented in this web page.

However, if option 2 is selected, Fig. 3, the user will have to supply information about the pregnant worker (in the x-ray department or Cath Lab facilities) and the Approved Dosimetry Service (ADS) providing the personal dosimeter reading. The user also has to provide information about

(a) the gestational age (in weeks),
(b) the occupational dose (in mGy_{TLD}),
(c) the number of months in the monitoring period,
(d) whether the staff member has been wearing a lead apron in the course of her work,
(e) the usual placement of the dosimeter (i.e. under or over the lead apron if worn), and
(f) the lead apron thickness (in mmPb).

Figure 3: Electronic form to the case study of the medical exposure of the pregnant patient



The program uses the personal dosimeter reading and the lead apron and TLD configuration information to calculate the fetal dose in the monitoring period.

Table 2 shows the summary of the information required by the "Dose Fetal Web" for each exposure type.

Table 2: Summary of the information required by the "Dose Fetal Web" to the dose fetal and radiation risks calculations.

Exposure Type	**Pregnant Information**	**Physical Quantity**	**Explanations**
Medical	Gestation Age (weeks) AP Thickness (cm) (or weight (kg) and height (m)) Fetal Depth (cm)	Entrance Surface Dose (ESD) (mGy)	Technical Parameters to the ESD estimation
Occupational	Gestation Age (weeks)	Occupational Dose (mGy_{TLD})	Lead apron and TLD configuration during the monitoring period

3. Results

Some illustrative hypothetical case studies were made with the program:

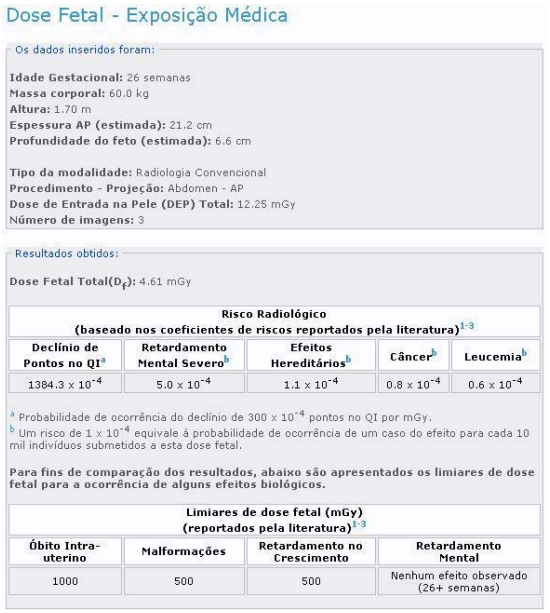
Example 1: Radiographic examination

A patient (60 kg and 1.70 m) who was 26 weeks pregnant had an AP abdominal examination for medical reasons. The following data was applied, as was showed in Fig. 2:

Peak tube voltage: 70 kVp
Total filtration: 3 mmAl
Focus-to-skin distance: 75 cm
Tube current and exposure time: 50 mAs
Number of exposures: 3

The patient thickness and the fetal depth obtained by the program were 21.2 cm and 6.6 cm respectively. The fetal dose calculated by the program was 4.61 mGy. The web page with the all calculated data is presented in Fig. 4.

Figure 4: Electronic form to the case study of the medical exposure of the pregnant patient, with the all information that was inputted and the results calculated by the program



Dose Fetal - Exposição Médica

Os dados inseridos foram:

Idade Gestacional: 26 semanas
Massa corporal: 60.0 kg
Altura: 1.70 m
Espessura AP (estimada): 21.2 cm
Profundidade do feto (estimada): 6.6 cm

Tipo da modalidade: Radiologia Convencional
Procedimento - Projeção: Abdomen - AP
Dose de Entrada na Pele (DEP) Total: 12.25 mGy
Número de imagens: 3

Resultados obtidos:

Dose Fetal Total(D_f): 4.61 mGy

Risco Radiológico (baseado nos coeficientes de riscos reportados pela literatura)[1-3]				
Declínio de Pontos no QI[a]	Retardamento Mental Severo[b]	Efeitos Hereditários[b]	Câncer[b]	Leucemia[b]
1384.3×10^{-4}	5.0×10^{-4}	1.1×10^{-4}	0.8×10^{-4}	0.6×10^{-4}

[a] Probabilidade de ocorrência do declínio de 300×10^{-4} pontos no QI por mGy.
[b] Um risco de 1×10^{-4} equivale à probabilidade de ocorrência de um caso do efeito para cada 10 mil indivíduos submetidos a esta dose fetal.

Para fins de comparação dos resultados, abaixo são apresentados os limiares de dose fetal para a ocorrência de alguns efeitos biológicos.

Limiares de dose fetal (mGy) (reportados pela literatura)[1-3]			
Óbito Intra-uterino	Malformações	Retardamento no Crescimento	Retardamento Mental
1000	500	500	Nenhum efeito observado (26+ semanas)

The fetal dose result obtained by the online program agrees with the published in the literature mean fetal dose 4.29 mGy.

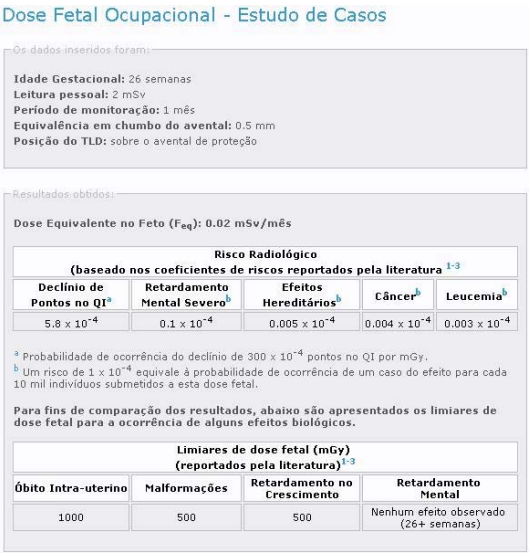
Example 2: Pregnant worker in Cath Lab facilities

The following data was applied, as was showed in Fig. 3:

Gestational age: 26 weeks
TLD dosimeter reading: 2 mGy_{TLD}
Monitoring period: 1 month
Lead apron and TLD dosimeter configuration: TLD was worn by the worker during that period outside the lead apron with 0.5 mmPb

The fetal equivalent dose calculated by the program was 0.02 mSv/month. The web page with the all calculated data is presented in Fig. 5.

Figure 5: Electronic form to the case study of the occupational exposure of the pregnant patient, with the all information that was inputted and the results calculated by the program



Dose Fetal Ocupacional - Estudo de Casos

Os dados inseridos foram:

Idade Gestacional: 26 semanas
Leitura pessoal: 2 mSv
Período de monitoração: 1 mês
Equivalência em chumbo do avental: 0.5 mm
Posição do TLD: sobre o avental de proteção

Resultados obtidos:

Dose Equivalente no Feto (F_{eq}): 0.02 mSv/mês

Risco Radiológico (baseado nos coeficientes de riscos reportados pela literatura [1-3]				
Declínio de Pontos no QI[a]	Retardamento Mental Severo[b]	Efeitos Hereditários[b]	Câncer[b]	Leucemia[b]
5.8×10^{-4}	0.1×10^{-4}	0.005×10^{-4}	0.004×10^{-4}	0.003×10^{-4}

[a] Probabilidade de ocorrência do declínio de 300×10^{-4} pontos no QI por mGy.
[b] Um risco de 1×10^{-4} equivale à probabilidade de ocorrência de um caso do efeito para cada 10 mil indivíduos submetidos a esta dose fetal.

Para fins de comparação dos resultados, abaixo são apresentados os limiares de dose fetal para a ocorrência de alguns efeitos biológicos.

Limiares de dose fetal (mGy) (reportados pela literatura)[1-3]			
Óbito Intra-uterino	Malformações	Retardamento no Crescimento	Retardamento Mental
1000	500	500	Nenhum efeito observado (26+ semanas)

The fetal equivalent dose result obtained by the online program agrees with the published in the literature mean fetal dose of 0.06 mSv/month.

4. Conclusions

This work will contribute for fetal dose and radiological risks evaluations of medical and occupational exposures of the pregnant women, as much by means of studies of hypothetical cases when for real situations of inadvertent exposure. For example, during the first weeks of pregnancy that is the period where the pregnancy can be unknown. These evaluations can benefit in the taking of decisions and the counselling the pregnant with regard to the effect of the ionizing radiation to the unborn child.

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