CALDose_X – a software tool for absorbed dose calculations in diagnostic radiology

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Abstract. Conversion coefficients (CCs) between absorbed dose to organs and tissues at risk and measurable quantities commonly used in X-ray diagnosis have been calculated for the last 30 years mostly with mathematical MIRD5-type phantoms, in which organs are represented by simple geometrical bodies, like ellipsoids, tori, truncated cylinders, etc. In contrast, voxel-based phantoms are true to nature representations of human bodies. The purpose of this study is therefore to calculate CCs for common examinations in X-ray diagnosis with the recently developed MAX06 (*M*ale *A*dult vo*X*el) and FAX06 (*F*emale *A*dult vo*Xel)* phantoms for various projections and different X-ray spectra and to make these CCs available to the public through a software tool, called CALDose_X (*CAL*culation of *Dose* for *X*-ray diagnosis).

KEYWORDS: Radiation protection, human phantoms, diagnostic radiology.

1. Introduction

Conversion coefficients (CCs) between absorbed or equivalent dose to organs at risk and measurable quantities commonly used in X-ray diagnosis have been calculated for the last 30 years mostly with mathematical MIRD-type phantoms. Kramer and Drexler [1] and Rosenstein [2] published independently organ doses in the MIRD5 phantom [3] for diagnostic radiology for the first time. Since then, comprehensive compilations of organ absorbed doses for the most important as well as for special examinations have been published for the ADAM and EVA phantoms [4] and other MIRD5-type phantoms, relating the quantities of interest to measurable quantities, like exposure in free air, entrance exposure on the surface of the patient or dose-area product [5, 6, 7].

Based on MIRD5-type phantoms, software tools for absorbed dose calculations have been developed, like PCXMC [8], which is a MC code using the whole MIRD5 phantom family [9] and applying scaling factors to modify the size of the phantoms, and like DoseCal [10], which uses the CCs determined for adults and children [5, 11], but this program does not scale for weight or size.

The development of tomographic or voxel-based phantoms began in the 80ies of the last century [12], but relatively few studies with respect to diagnostic radiology have been published with these phantoms over the last 20 years and if so, then mainly about special radiographic examinations. None of them presented a comprehensive set of voxel-based CCs for the most important X-ray examinations.

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The purpose of this study is therefore

a) to calculate CCs for the most common examinations in X-ray diagnosis with the recently developed MAX06 and FAX06 phantoms [13] for various projections and different X-ray spectra and
b) to make these CCs available to the public through a software tool, called CALDose_X (*CAL*culation of *Dose* for *X*-ray diagnosis), for the calculation of organ and tissue absorbed dose to the patient to be used in daily routine work by radiological departments of hospitals, health services, regulatory authorities, educational programs, etc.

2. Materials and methods

The EGSnrc Monte Carlo [14, 15] code was used to calculate organ and tissue absorbed doses in the FAX06 and the MAX06 phantoms and to normalize them to incident air kerma (INAK), entrance surface air kerma (ESAK) and air kerma-area product (KAP), all measurable quantities used in X-ray diagnosis and defined by the International Commission on Radiation Units and Measurements (ICRU) [16]. The CCs were calculated for X-ray examinations of the head, spine, throat, chest, stomach, duodenum, abdomen and pelvis for 40 different X-ray spectra between 50 and 120 kVp, for constant potential generators, X-ray tubes with 17° target angle, beam filtration between 2 and 5 mm Al, various projections for standard field positions typical for the corresponding examination. Additionally, field positions were calculated which deviate 4 cm from the standard position in each direction in order to provide an idea, how relatively small changes of the organ position relative to the beam volume can significantly influence the organ absorbed dose.

For each MC simulation of a diagnostic X-ray examination, average absorbed doses (kerma) have been calculated in the following 29 organs and tissues of the MAX06 and the FAX06 phantoms: adrenals, bladder wall, brain, oral mucosa, colon wall, breasts, kidneys, liver, lungs, muscle tissue, oesophagus, ovaries, testes, pancreas, small intestine wall, skin, spleen, stomach wall, salivary glands, thymus, thyroid, extra-thoracic region, uterus, prostate, heart wall, lymphatic nodes, gall bladder wall, bone surface cells (BSC) and red bone marrow (RBM). Absorbed dose to the mouth cavity was taken as surrogate absorbed dose to the oral mucosa. The 29 organs and tissues are those specified by the International Commission on Radiological Protection (ICRP) for the calculation of the effective dose [17].

Diagnostic X-ray examinations represent quite inhomogeneous exposures to the human body. Depending on its location with respect to the boundaries of the irradiated body volume, a specific organ or tissue can be exposed by primary radiation completely, partly or not at all. From the assumption of a linear, non-threshold, dose-response relationship [17] follows the concept of average absorbed dose and this study applies this concept to all of the above mentioned organs and tissues independent from their location with respect to the beam boundaries, except for the RBM, the BSC and the skin. Among the tissues which are distributed over the whole body, the RBM, the BSC and the skin have the greatest risk factors. For example, they are listed in the main group of tissues which are to be taken into account for the determination of the effective dose [17], the RBM being even among those tissues with the greatest tissue weighting factor.

Bones, and with them the RBM and the BSC, are distributed very heterogeneously throughout the human body. For diagnostic X-ray examinations the average whole body RBM or BSC absorbed doses are usually much smaller than the absorbed doses to those parts of these skeletal tissues which are located inside the irradiated volume of the body. Consequently, in this study the absorbed doses to the RBM and the BSC are determined as maximum average absorbed doses selected from the RBM and BSC absorbed doses to the skull, the mandible, the ribcage (ribs, sternum, clavicles and scapulae), the spine, the pelvis, upper arm bones and upper leg bones. Depending on the X-ray projection it can still happen that some of these bones or bone groups are located partly inside or outside the beam.

Therefore CALDose_X outputs these RBM and BSC absorbed doses as “mainly in beam volume”, which makes them more suitable for risk estimates than the RBM and BSC absorbed doses averaged over the whole body.

Similar considerations apply to the skin. For extreme partial body exposures, like in interventional radiology, even tissue damage may occur while at the same time the average whole body skin absorbed dose is still relatively small. In this study, a maximum skin entrance absorbed dose is determined, which is the average absorbed dose to a 7.2 cm x 7.2 cm square of skin tissue centered around the central axis of the beam where it enters the phantom. This quantity is considered to be more appropriate for risk estimates than the skin absorbed dose averaged over the whole body surface.

Besides the average absorbed organ and tissue doses, CALDose_X also provides a weighted whole-body FAX06 and MAX06 dose, respectively. For the calculation of these quantities whole-body RBM, BSC and skin absorbed doses have been used. The arithmetic mean of these two quantities is the effective dose [17]. However, the effective dose cannot be applied to an individual patient, because the tissue weighting factors have been averaged over both sexes and all age groups. Therefore, CALDose_X also provides an age- and sex-specific estimate of the patient’s cancer risk based on risk weighting factor from the BEIR VII report [18].

The complete description of the exposure model, including a comprehensive analysis of the uncertainties involved, can be found elsewhere [19].

3. Results

After having been started, CALDose_X expects to be informed about the name of the institution and the name, the age and the sex of the patient .

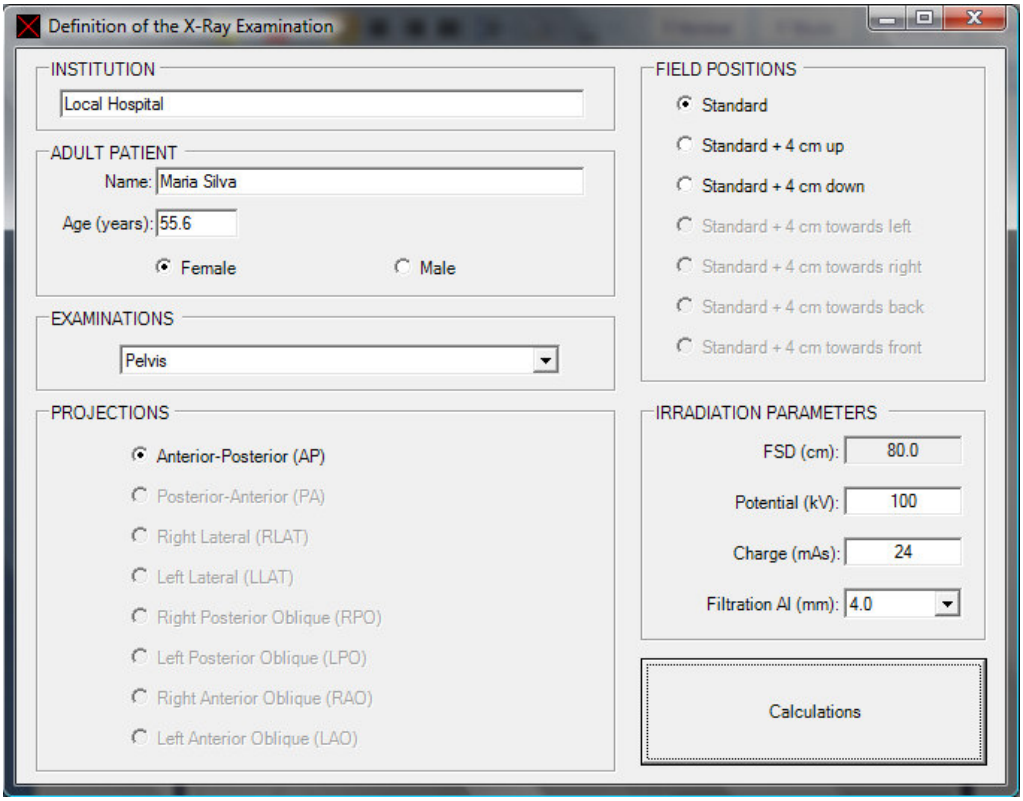

Fig. 1. First CALDose_X form: Definition of X-ray examination

From a drop down window the user then selects one of 10 examinations, which is the lumbar spine radiograph shown here as an example. Next follows the selection of the projection and the position of the field. “Standard” represents the field location mostly used for this type of examination according to studies mentioned above and based on textbooks for X-ray practitioners. For some examinations CALDose_X offers alternatively field locations with a 4 cm shift in a certain direction to show the effect on organ absorbed doses if the field location is “off Standard”.

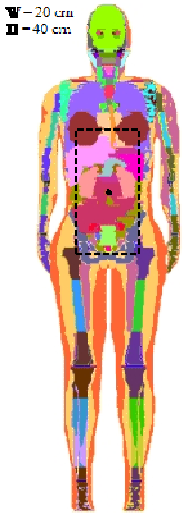

Fig. 2a. Frontal view of FAX06 phantom and X-ray field in detector plane

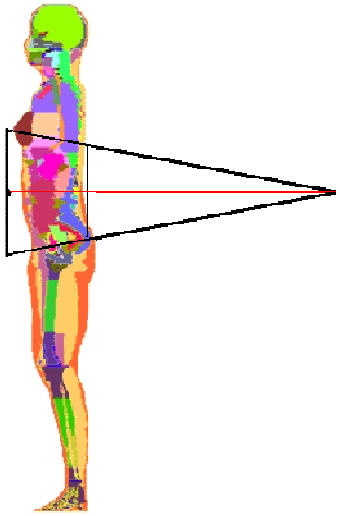

Fig. 2b. Lateral view of FAX06 phantom and X-ray beam

Once the field position has been selected, two images pop up, like the examples shown in figures 2a and 2b, which show the phantom and the position of the X-ray beam relative to the body. Field height and field width are given in cm for the plane of the detector (film). The focus to skin distance (FSD) for the selected examination appears in the first field of the area called “irradiation parameters”. Users who only want to visualize the selected examination could close CALDose_X at this point.

However, if the calculation of the ESAK or organ and tissue absorbed doses are requested, then the user has to fill in the tube potential in kV with a number between 50 and 120 and the charge in mAs. The filter between 2 and 5 mm Al can be selected from the drop down window.
After having clicked on the “Calculate” button, the form shown in figure 3 appears on the screen. The user has now the following options:

a) INAK (output) = to calculate the INAK and the ESAK based on the output of the user’s X-ray unit,

b) ESAK (INAK, KAP) = to calculate the ESAK based on measured values for INAK or KAP,

c) Absorbed Dose (INAK, ESAK, KAP) = to calculate organ and tissue absorbed doses based on INAK, ESAK or KAP, or

d) CC (INAK, ESAK, KAP) = to display just the conversion coefficients.

In the example shown in figure 3 the first option has been chosen, which presumably represents the most frequent case in radiodiagnosis. The user has to fill in the values for the tube potential in kV and for the output in µGy/mAs at 1m distance from the tube. CALDose_X offers the possibility to save the output curve for future calculations.

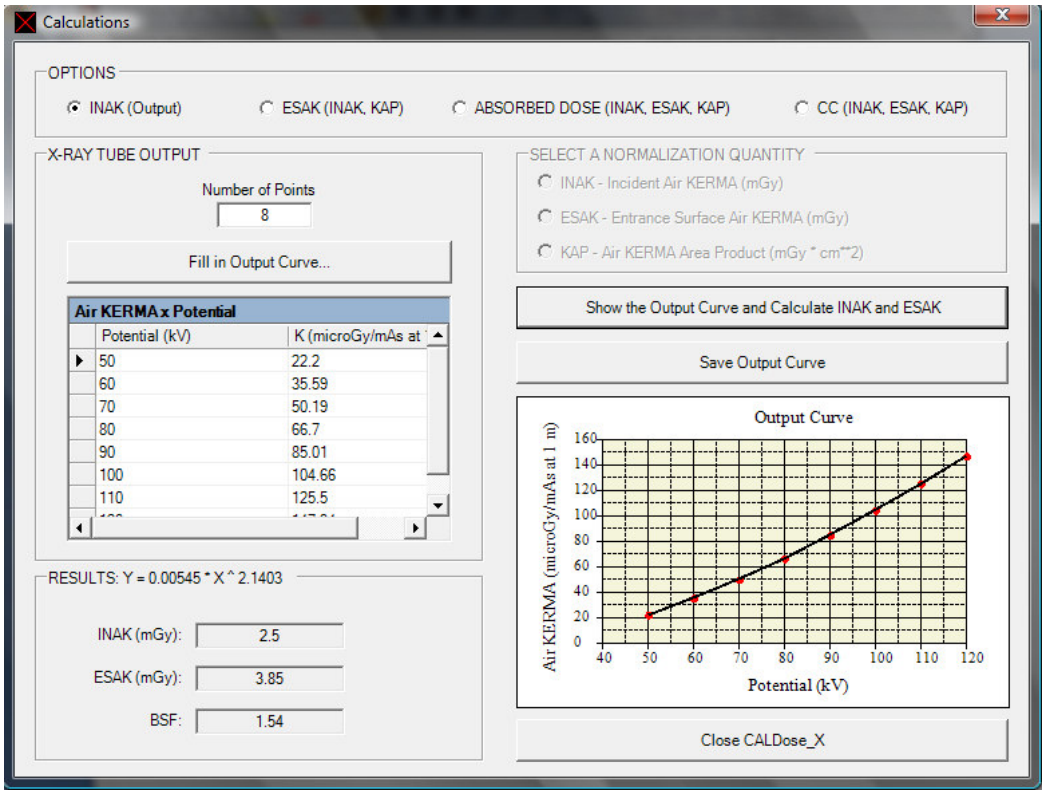

Fig. 3. Second CALDose_X form: Calculation of INAK and ESAK

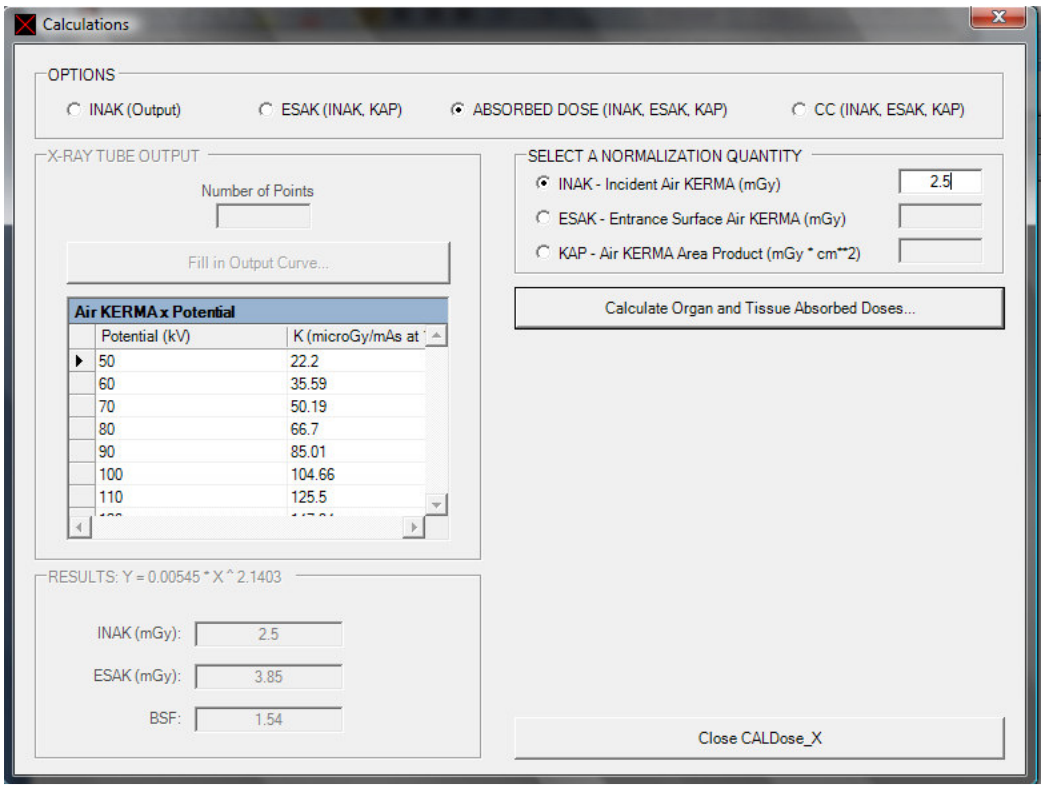

Fig.4. Third CALDose_X form: Selection of organ and tissue absorbed dose calculation based on INAK

After having clicked on the button “Show the output curve and calculate INAK and ESAK”, CALDose_X shows a graph of the output curve, calculates and shows the INAK and the ESAK for the FSD given in the previous form. The ESAK is the INAK multiplied with the backscatter factor (BSF), which is provided by with the Monte Carlo calculation.

In a last step, the user should now click on the option “Absorbed Dose (INAK, ESAK, KAP)” and select one of the measurable quantities INAK, ESAK or KAP. The first two are automatically filled in if option a) was selected before. Otherwise, like for the KAP, also for INAK or ESAK values have to be filled into the corresponding fields to be seen in figure 4. A click on “Calculate” produces table 1, which shows the names of the institution, sex, age and name of the patient in the header, then irradiation parameter for the examination and finally organ and tissue absorbed doses in mGy together with the statistical error of the Monte Carlo calculation. At the end of the list with organ and tissue absorbed doses, CALDose_X prints out a “Weighted Female Whole Body dose”. A similar quantity appears at the end of the list for the MAX06 phantom. The arithmetic mean of the two weighted doses divided gives the effective dose. Additionally, the list provides the risks for cancer incidence and cancer mortality.

TABLE I. Organ and tissue absorbed doses and cancer risks

INSTITUTION: Local Hospital
PACIENT: Female AGE: 55.6 years
NAME: Maria Silva
Date: 26/6/2008
EXPOSURE CONDITIONS:
FAX06: PELVIS, ANTERIOR-POSTERIOR (AP)
IMAGE BEHIND THE BODY
100 kVcp 4.0 mm Al 17 Deg Tungsten IPEM/SR78
MEAN SPECTRAL ENERGY: 51.4 keV ABSORBED FRACTION: 0.57
SOURCE-TO-DETECTOR (FILM): 106 cm
SOURCE-TO-SKIN: 80 cm
FIELD SIZE IN DETECTOR PLANE: 40 cm x 35 cm
FIELD POSITION: STANDARD
CHARGE: 24 mAs

ORGAN OR TISSUE ABSORBED DOSE

ORGAN/TISSUE	mGy	%
ESAK	3.85	1.32
ADRENALS	0.07	7.64
BLADDER WALL	1.83	0.82
COLON WALL	1.12	0.35
BREASTS	0.00	4.69
KIDNEYS	0.26	0.87
LIVER	0.04	0.95
LUNGS	0.00	3.27
OVARIES	1.49	1.72
PANCREAS	0.08	2.30
SMALL INTESTINE WALL	1.45	0.24
SKIN ENTRANCE 7.2cm X 7.2cm	3.99	1.32
SPLEEN	0.07	2.42
STOMACH WALL	0.07	2.18
UTERUS	1.28	0.71
LYMPHATIC NODES	1.44	0.34
BSC DOSE MAINLY IN BEAM VOLUME	3.30	0.19
RBM DOSE MAINLY IN BEAM VOLUME	1.19	0.24
WEIGHTED FEMALE WHOLE BODY DOSE	0.43	0.46

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RISK OF CANCER INCIDENCE                    3.93 CASES   PER 100000
RISK OF CANCER MORTALITY                    2.14 CASES   PER 100000
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Options b) and d) are self-evident and are described in the user guide, which will be distributed with the CALDose_X software package

4. Conclusion

CCs between organ and tissue absorbed doses and the normalization quantities INAK, ESAK and KAP have been calculated with the MAX06 and the FAX06 phantoms for examinations frequently performed in X-ray diagnosis. Based on these CCs, the software tool CALDose_X has been developed, which can be used

- to calculate the INAK based on the output curve of the X-ray equipment,
- to assess the ESAK in order to control compliance with diagnostic reference levels,
- to calculate organ and tissue absorbed doses for patients with anatomies similar to the MAX06 and the FAX06 phantoms,
- to assess the effective dose and/or the patient's cancer risk,
- to demonstrate how organ and tissue absorbed doses, i.e. the radiation risk for the patient, depend on the proper selection of the exposure parameters. This information can be used in educational programs to train radiologists and technicians to understand how to perform X-ray examinations with the minimum exposure to the patient,
- to compare organ and tissue absorbed doses, effective doses or radiation risks from different radiological procedures, or from different X-ray units, or from different hospital, etc., to identify high and low risk examinations, or cases of good and bad practice and
- to make risk assessments for surveys on radiological exposures, taking into account risk factors for the age and gender distribution of the patient population under consideration.

Compared to MIRD5-based software tools (PCXMC and DoseCal) for diagnostic radiology, CALDose_X presents two improvements: First, using voxel phantoms allows for organ and tissue absorbed dose calculations based on a true to nature representation of the human anatomy and second, the cancer risk assessment offers an alternative to the effective dose, which cannot be used for an individual patient.

CALDose_X stands in the tradition of software tools developed earlier. It represents an improvement compared to them, but on the other hand it is only another milestone towards the aim to make software tools for diagnostic radiology every time more patient-specific.

Consequently, CALDose_X has to be understood as an open project, which will be updated from time to time with new features, like patient-specific fat distributions, age-related anatomical changes during adult life span, children phantoms, improved skeletal dosimetry, other types of examinations, etc.

CALDose_X is available from the following website of the Federal University of Pernambuco: http://www.grupodoin.com

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