Calculation of radiation doses to patients in diagnostic radiology using PCXMC software

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Abstract: X-ray radiology may exhibit negative biological impacts. PCXMC is a Monte Carlo phantom based computational program used in clinical environments to calculate radiology radiation dose and fatal cancer risks received by such examinations. PCXMC allows for numerous X-ray beam, patient and simulation inputs and outputs absorbed dose, effective dose, and risk of exposure induced death (REID) for various cancers. Clinically applicable PCXMC outputs have not been yet been comprehensively compiled for educational use. PCXMC was used to investigate relationships between various clinically valid beam parameters (energy, intensity), planar view geometries (AP/PA/LATR/LATL whole body and anatomy specific views), and patient statistics (age, weight, gender, ethnicity), as supplied by medical professionals, peer-reviewed database sources and government statistics. Dosimetric and REID outputs were recorded. For whole body planar X-rays, males exhibited higher absorbed (mean 198% m/f) and lower effective (mean 90% m/f) doses versus females. REID for different organs were raised within the beam area and on the beam incident body side (illustrative 2400% increased REID for liver in whole body male LATR versus LATL). Varying beam height and width was seen to affect dose as a function of the height-width aspect ratio of the anatomy involved. Euro-Americans had higher total REID than Asian and Finnish counterparts (37.4yo male 1.18/1.03/1 respective REID ratio), with REID also varying non-linearly with age. PCXMC proved to be a versatile modelling tool from which a comprehensive database could be constructed but was limited in not modelling realistic beam collimation.

Introduction

- X-ray dosimetry and health risks can be assessed using computational simulated biological models such as PCXMC.
- PCXMC uses a Monte Carlo method of assessing X-ray interactions with a phantom.
- Outputs include absorbed dose, effective dose and **r**isk of X-ray **e**xposure **i**nduced cancer **d**eath (REID).

In this study:

1. Dose and REID were assessed for AP/PA/LATL/LATR whole body views to determine relative organ radiosensitivity.
2. Dose and REID were assessed for views and associated tube settings commonly used in diagnostic radiology
3. Dose and REID were assessed in detail for the chest PA view, varying beam area, patient age and ethnicity.

Method

PCXMC was used to determine absorbed dose, effective dose and REID for several anatomical views as shown in **Table 1**. These were simulated for both "male" and "female" phantoms, by using view parameters in conjunction with common parameters shown in **Table 2** to define phantom characteristics and inform beam geometry. The beam was aligned with anatomy of interest using the simulated view as shown in **Figure 1**.

Table 1: Radiography views and associated parameters as defined by Radiopaedia.[3] Whole-body parameters were defined by the researcher to ensure good radiation coverage and penetration. PEID (Phantom exit to image distance was 0 in all cases). Where a range of values was given, the mean was used.

Anatomy	Aspect	Beam Orientation	Detector Size (cm)	Exposure (kVp)	Exposure (mAs)	SID/FID (cm)
W Body	AP	Portrait	180 x 65	75	50	100
W Body	PA	Portrait	180 x 65	75	50	100
W Body	LATL	Portrait	180 x 65	75	50	100
W Body	LATR	Portrait	180 x 65	75	50	100
Skull	AP	Portrait	24 x 30	75	8-10	100
Skull	PA	Portrait	24 x 30	75-80	20-25	100
Skull	LATL	Landscape	24 x 30	60-70	10-20	100
L Spine	AP	Portrait	35 x 43	70-80	40-60	110
Chest	AP	Varies	35 x 43	100-110	4-8	180
Chest	PA	Varies	35 x 43	100-110	4-8	180
Chest	LATL/LATR	Portrait	35 x 43	100-110	8-12	180
Abdomen	AP	Varies	35 x 43	70-80	30-120	100
Abdomen	PA	Varies	35 x 43	70-80	30-50	100
Pelvis	AP	Landscape	35 x 43	70-80	20-30	100-120
Femur	AP	Portrait	30 x 43	65-70	8-12	100

Table 2. Common simulation parameters for varying anatomical views. Weight, height, and age characteristics were informed by the Irish average from CSO and NCD-RisC data.[1][2]

Max Energy (keV)	Number of Photons Simulated	Filtration (mm Al)	Anode Angle (°)	Ethnicity	Male Height (cm)	Male Weight (kg)	Female Height (cm)	Female Weight (kg)	Age (y)
150	200,000	2.5	13.5	Euro-American	179	90.0	164.5	73.6	37.4

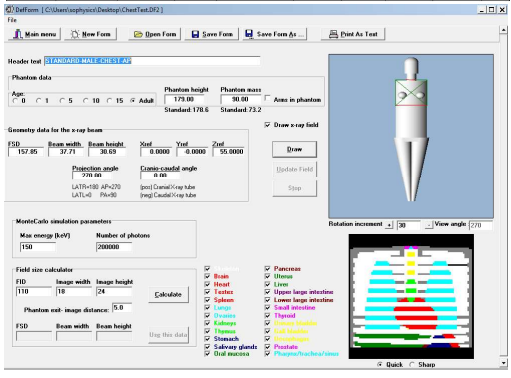

Figure 1. Examination data tab in PCXMC showing an example chest AP view, with settings (left), beam geometry (top right), and image simulation (bottom right).

Adjusting collimation of both beam breadth (transverse across the phantom) and width (on the patient z-axis) as measured at the detector were assessed for both male and female phantoms for chest PA. As PCXMC does not accurately simulate the behaviour of a real X-ray tube with regards to collimation (PCXMC "collimates" beams by reducing beam height and width, without automatic adjustment of output air kerma), a Shimadzu MobileDaRt Evolution MX8 mobile X-ray system was used together with a RaySafe X2 radiation meter to measure air kerma values which were input to PCXMC for several beam sizes.

Male REID was assessed for chest PA varying ethnicity (Euro-American, Asian and Finnish) for constant age 37.4 years, and age groups (16, 20, 30, 40, 50, 60, 70, 80, 90, 100) for Euro-American ethnicity.

[1]: NCD-RisC (2017). *Worldwide trends in body-mass index, underweight, overweight, and obesity from 1975 to 2016: a pooled analysis of 2416 population-based measurement studies in 128.9 million children, adolescents, and adults.* The Lancet. 390(10113), pp. 2627–2642
[2]: Central Statistics Office (2016). *Census of Population 2016 – Profile 3 An Age Profile of Ireland*, [Online] Available at: <https://www.cso.ie/en/releasesandpublications/ep/p-cp3oy/cp3/aad/> Accessed 4th February 2023
[3]: Radiopaedia (2023). *About Radiopaedia.org*. Radiopaedia Blog RSS. [Online] Available at: <https://radiopaedia.org/about?lang=us> Accessed 4th February 2023

Results & Discussion

1. Dose and REID for male and female whole-body views

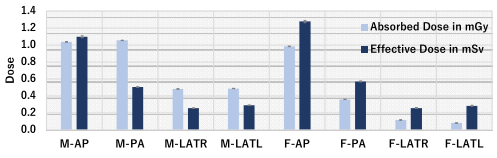

Figure 2. Graphs of absorbed dose and effective dose for AP, PA, LATL and LATR whole-body views of a male and female phantom, respectively. M/F denote male and female phantoms.

- Male absorbed dose was greater than effective dose in all views except AP.
- Female absorbed dose was less than effective dose in all views.
- Male absorbed dose was higher than for females, likely due to greater height and weight of males.
- Male effective dose was similar or less than for females in all views. Broader male bone structure is suggested as a filtration material to reduce effective dose in radiosensitive organs.

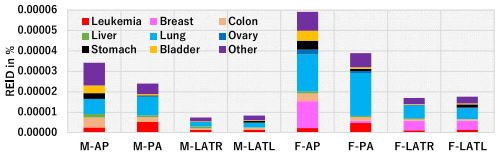

Figure 3. Risk of exposure induced death in % for cancers in various organs for whole-body views in AP, PA, LATL, and LATR orientations for a male and female phantom, respectively. M/F denote male and female phantoms.

- AP and PA aspects had the highest REID, corresponding to higher absorbed and effective dose.
- Females showed higher REID, mirroring higher effective doses.
- Lung cancer was dominant for both males and females.
- Females exhibited high additional risk for fatal breast cancer.
- REID was higher for organs on the beam incident body side.

2. Dose and REID for male and female anatomical views

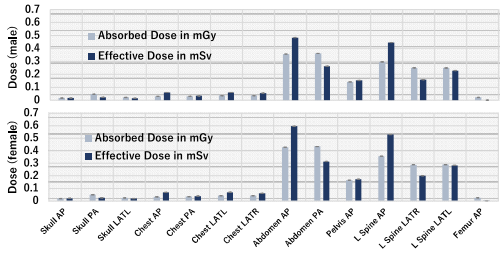

Figure 4. Graphs of absorbed dose and effective dose for common radiographic views of male and female phantoms, respectively.

- Both male and female phantoms observed the same general trend in absorbed and effective doses for each view.
- Females had increased absorbed and effective dose to males.
- Abdomen and L spine exhibited the highest absorbed and effective dose rates due to the view's high mAs exposure.
- Femur and skull exhibited extremely low absorbed and effective dose, likely due to lack of radiosensitive regions in the first case, and potential shielding by the skull in the latter case.

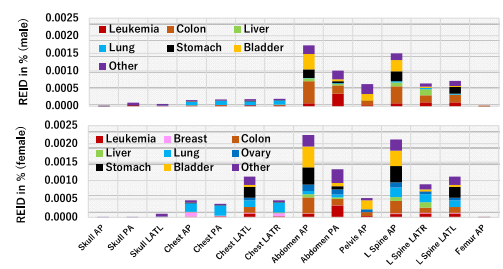

Figure 5. REID in % for cancers in various organs for several anatomical views for male and female phantoms, respectively.

- "Other" cancers dominated REID for skull and femur views. These views also represented the lowest REID.
- Abdomen AP and L Spine AP views had the highest REID, likely due to high mAs exposure required by this view.
- Chest AP and PA views had the highest lung cancer REID.
- Chest LATL's primary REID was stomach, whereas chest LATR had a much smaller stomach REID, coinciding with stomach being biased towards the left side of the body.
- Breast cancer REID in chest AP views for females was increased relative to chest PA views.

3. Dose and REID varying beam area for chest PA view

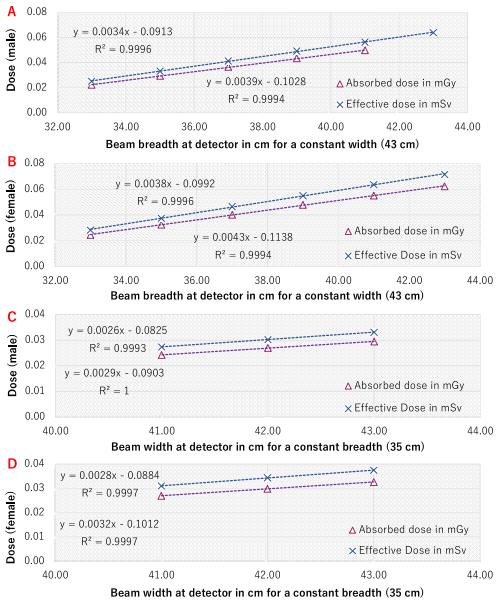

Figure 6. Absorbed and effective dose for varying beam breadth for constant width (A & B), and varying beam width for constant breath (C & D) for a chest PA exam for male (A, C) and female phantoms (B, D), respectively.

- Increasing breadth and width both increased absorbed and effective dose.
- Increasing breadth had the greater effect (breadth slope = 0.0034 (M) & 0.0038 (F) mGycm^{-1} versus width slope = 0.0026 (M) & 0.0032 (F) mGycm^{-1}). This was due to the greater constant width value for varying breadth.
- It is suggested that where patient weight is considered proportional to width, collimating for breadth is more effective at reducing dose than collimating for width.

4. Ethnicity and Age in Chest PA

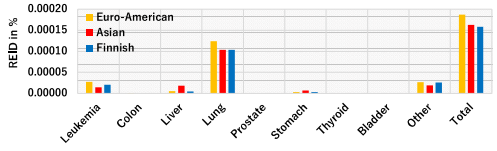

Figure 7. Risk of exposure induced death in % for cancers in various organs for various phantom ethnicities for a male phantom, 37.4 years old with chest PA parameters.

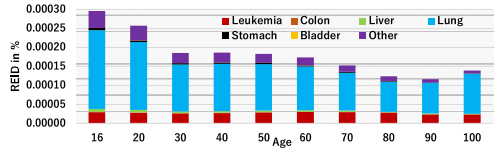

Figure 8. Risk of exposure induced death in % for cancers in various organs for various ages for a male phantom of Euro-American ethnicity with chest PA parameters.

- Finnish ethnicity had lowest REID. Euro-American had highest.
- Asian REID closely matched Finnish REID.
- The Asian phantom had elevated liver REID.
- The Euro-American phantom had elevated lung REID.

- REID declined rapidly from 16-20-30, likely due to increased radiosensitivity and an increased life expectancy in youth.
- REID levels off in middle age and declines in the elderly. This is assumed to result from overlap of cancer latency periods in middle age and thus a long period in which radiation induced fatal cancer may develop.

Conclusion

- Male phantoms had higher whole body absorbed dose and lower effective dose values.
- This did not necessarily hold true for other anatomical views, e.g. females had higher abdomen AP absorbed dose than males.
- Fatal cancers were generally more likely within the beam area and closer to the beam incident side of the body.
- There was pronounced REID dependency on age and ethnicity.
- PCXMC was a dynamic and powerful tool but there was difficulty in modelling collimation without using physically measured kerma values as inputs.

- Further studies may explore more views to assess dose and REID across different ethnicities and ages, especially children.