CT Radiation Dosimetry Study Using Monte Carlo Simulation and Computational Anthropomorphic Phantoms

by

Yakun Zhang

Graduate Program in Medical Physics
Duke University

Date:_______________________
Approved:

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Ehsan Samei, Supervisor

___________________________
W. Paul Segars

___________________________
Robert Reiman

Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the Graduate Program in Medical Physics in the Graduate School of Duke University

2012
ABSTRACT

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Abstract

There are three main x-ray based modalities for imaging the thorax: radiography, tomosynthesis, and computed tomography (CT). CT perhaps provides the highest level of feature resolution but at notably higher radiation dose, which has increased the concern among radiation protection professionals. Being able to accurately assess the radiation dose patients receive during CT procedures is a crucial step in the management of CT dose. To identify the best imaging modality for patients, the American College of Radiology published the guiding principle of “The right exam, for the right reason, at the right time”. To implement this principle in making an appropriate choice between standard chest projection imaging, tomosynthesis, and CT, the organ and effective dose for each modality should be accurately known. This thesis work attempted to explain the effect on dose results when choosing different types of computational phantoms used in CT dosimetry; this work also compared radiation dose across three main x-ray based modalities on one common platform for different body shape adults.

The first part of this thesis compared organ doses, effective doses, and risk indices from 13 representative adult CT protocols using four types of reference phantoms (XCAT, ICRP 110, ImPACT, and CT-Expo). Despite closely-matched organ mass, total body weight, and height, large differences in organ dose exist due to
variation in organ location, spatial distribution, and dose approximation method. Dose differences for fully irradiated radiosensitive organs were much smaller than those for partially irradiated organs. Weighted dosimetry quantities including effective dose, male risk indices, $k$ factors, and male $q$ factors agreed well across phantoms. The female risk indices and $q$ factors varied considerably across phantoms.

The second part of this thesis estimated organ doses, effective doses and risk indices for the three clinical X-ray imaging techniques (chest radiography, tomosynthesis, and CT) using 59 anatomically variable voxelized phantoms and Monte Carlo simulation methods. The average effective dose of the chest posteroanterior examination was found to be 0.04 mSv, which was 1.3% that of the chest CT examination. The average effective dose of the chest tomosynthesis examination was found to be about ten times that of the chest posteroanterior examination and about 12% that of the chest CT examination. With increasing patient average chest diameter, both the effective dose and risk index for CT increased considerably in an exponential fashion, while these two dose metrics only increased slightly for radiographic modalities and for chest tomosynthesis. Effective and organ doses normalized to mAs all illustrated an exponential decrease with increasing patient size. In conclusion, patient body size has a much greater impact on radiation dose of chest CT examinations than chest radiography and tomosynthesis. Patients of different sizes should be considered differently when choosing the best thoracic imaging modality.
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1. Introduction

Compared to the overlaying projected anatomy from conventional radiography, computed tomography (CT) has provided great diagnostic accuracy to the medical imaging world. However, it also introduces much more radiation exposure to the public, which has gained increased attention from the general public and health care providers. Therefore, it is important to be able to accurately estimate the radiation dose that patients receive during CT procedures so that any potential risk can be estimated and minimized.

Computational anthropomorphic phantoms combined with Monte Carlo simulation of radiation transport have proven to be an accurate and reliable method to estimate organ doses during CT examinations. Such phantoms have evolved from the original stylized phantoms, to voxelized phantoms, and to more advanced hybrid phantoms. Some comparisons between hybrid and stylized phantoms used in CT dosimetry have been made, but these comparisons included only limited examination types, leaving out some other important and routinely used CT examination, such as liver examinations. Part one of this thesis was to extend the earlier comparison efforts to four types of widely used reference phantoms, to a wide range of body and neurological examination types, and to dose and risk conversion coefficients.

One lower dose imaging technique—tomosynthesis, which can also provide slice-by-slice anatomical information, was re-introduced to the medical imaging world for an
alternative to CT. Application of tomosynthesis on screening and detection of lung nodules had been proposed because of its lower dose to radiosensitive organs lungs and breasts as well as its reasonable detectability. It is desirable to compare the radiation dose between chest CT and tomosynthesis on one common simulation platform across different patient body shapes, which has not been done before, to allow health care professionals to make informative decision on the best imaging modality for individual patient. Part two of this thesis compared organ doses, effective doses, and risk index between three x-ray based modalities for imaging the thorax: radiography, tomosynthesis, and CT.
2. Organ doses, effective doses, and risk indices in adult CT: Comparison of four types of reference phantoms across different examination protocols

2.1 Introduction

Over the past few decades, technological advances in x-ray computed tomography (CT) have made CT an essential diagnostic imaging tool. While this technology is bringing convenience and high quality tomography to the medical imaging world, it also introduces radiation exposure to the public. From the data published in 2006, the use of CT has increased at a rate of 8 to 15% per year for the last 7 to 10 years. In 2006, nearly half of the total medical radiation exposure was from CT. This has increased concern about CT imaging among radiation protection professionals as well as the general public. Therefore, it is important to be able to accurately estimate the radiation dose that patients receive during CT procedures so that any potential risk can be estimated and minimized.

Computational anthropomorphic phantoms combined with Monte Carlo simulation of radiation transport have proven to be an accurate and reliable method to estimate organ doses during CT examinations. Such phantoms have evolved from the original stylized phantoms, to voxelized phantoms, and to more advanced hybrid phantoms. Stylized phantoms define the organs and structures in the human body

1 This chapter is based on a manuscript with the same title published in the journal *Medical Physics*
through mathematical equations and simple geometric primitives. While highly flexible, stylized phantoms are limited in their ability to model the complexities of the human anatomy accurately.\textsuperscript{25, 26} To overcome the unrealistic nature of the stylized phantoms, voxelized phantoms have been developed over the last 20 years. These phantoms are based directly on segmented patient data from high resolution MRI or CT whole body scans, and have a high degree of realism. However, voxelized phantoms do not have the flexibility of stylized phantoms and cannot be easily used to model anatomical variations. To overcome this limitation, more advanced phantoms, hybrids of stylized and voxelized phantoms seeking to combine the advantages of both have been developed by several research groups.\textsuperscript{23, 24, 27} Hybrid phantoms are also based on segmented tomographic data of real patients. However, the segmented data are further used to generate polygon mesh surfaces, which are then fitted to sophisticated mathematical descriptors such as non-uniform rational B-splines (NURBS). They represent anatomy realistically since they are based on tomographic data from real patients, while at the same time they offer the flexibility to model variations in anatomical geometry.

Some comparisons between hybrid and stylized phantoms used in CT dosimetry have been made by Liu \textit{et al} and Lee \textit{et al}.\textsuperscript{10, 11, 15} However, earlier studies included only limited examination types, leaving out some other important and routinely used CT examinations, such as liver examinations. Furthermore, in the clinical environment, the
effective dose is often estimated by a dose length product (DLP) to effective dose conversion coefficient, called the $k$ factor. These earlier studies did not examine the choice of phantoms on the resulting dose conversion coefficients. In addition, comparisons between anatomically-realistic reference phantoms developed by different research groups have not yet been explored.

The purpose of this study was to extend the earlier comparison efforts to four types of widely used reference phantoms, to a wide range of body and neurological examination types, and to dose and risk conversion coefficients.

### 2.2 Methods

Figure 1 demonstrates the methodology used in this study. Four types of reference phantoms were employed: male and female hybrid phantoms in the XCAT family,$^{24}$ male and female voxelized phantoms provided in ICRP publication 110,$^{21}$ the hermaphrodite stylized phantom used in the ImPACT CT dose spreadsheet,$^{28}$ and male and female stylized phantoms used in the CT-Expo dose spreadsheet. For the XCAT$^{24}$ and ICRP 110 phantoms,$^{21}$ a validated Monte Carlo program modeling a 64-slice CT scanner (LightSpeed VCT, GE Healthcare, Waukesha, WI) was employed to simulate organ doses, which were then used to calculate effective doses, risk indices, and conversion coefficients from DLP to effective dose and risk index ($k$ and $q$ factors). For the ImPACT and CT-Expo phantoms, organ doses were obtained directly from their
associated dosimetry spreadsheets for the same CT scanner model, which were then used in the effective dose and risk index calculations.

Figure 1: Flow chart of the methodology used in this study. RI: risk index; ED: effective dose.

Figure 2: Lateral and frontal views of the four types of phantoms used in this study. (a) and (b): XCAT reference male and female hybrid phantoms after voxelization. (c) and (d): ICRP 110 reference male and female voxelized phantoms. The organs were
relabeled to be consistent with the XCAT phantoms. (e): ImPACT stylized/mathematical hermaphrodite phantom. (f) and (g): CT-Expo male and female stylized/mathematical phantoms.

2.2.1 Computational Phantoms

The four types of reference phantoms used in this study are detailed below. Their organ masses are tabulated in Table 1.

2.2.1.1 XCAT hybrid phantoms

The first set of phantoms was the reference male and female extended cardiac-torso (XCAT) phantoms (Figures 2a and 2b).\textsuperscript{24} The XCAT reference phantoms were initially created from the Visible Human anatomical data distributed by the National Library of Medicine (NLM).\textsuperscript{29} Segmentation of anatomical structures was applied semi-automatically by using a tablet PC with the help of a custom graphical application IMAGESEGMENT (RAI Laboratories, Duke University, Durham, NC, USA). The resulting segmented structure was converted to a 3D polygon model, and later fitted to cubic NURBS surfaces for a more compact mathematical description of the objects. Brains were modeled separately using MRI data of a normal male subject. After segmentation and conversion to a polygon model of the brain, subdivision surfaces replaced NURBS surfaces in order to more accurately represent the arbitrary topological structure in the brain.\textsuperscript{24}
The NURBS based phantoms developed from the Visible Human data were subsequently modified to match ICRP reference values. The body measurements and organ volumes were first matched to a 50th percentile (height and weight) male and female with desired data obtained using the survey data of US adults from the PEOPLESIZE program (http://www.openerg.com/psz/index.html). The organ masses were then matched to ICRP publication 89 values. Thus, the resulting phantoms were named reference male and female phantoms in the XCAT phantoms family. In the voxelized versions of the XCAT phantoms, skin was modeled as a single voxel layer on the surface, which caused the skin mass to be higher than the ICRP 89 reference mass.
Table 1: Organ masses for the four types of reference phantoms employed in this study. Reference organ masses published in ICRP 89 are also listed for comparison. Note that the CT-Expo male and female phantoms were matched to ICRP publication 23.

<table>
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<th>XCAT reference female</th>
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<th>ICRP110 reference female</th>
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<td>73000</td>
<td>60000</td>
<td>70910</td>
<td>70450</td>
<td>59193</td>
<td>73000</td>
<td>60000</td>
<td></td>
</tr>
<tr>
<td>weight</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>height (cm)</td>
<td>176</td>
<td>163</td>
<td>176</td>
<td>163</td>
<td>-</td>
<td>170</td>
<td>160</td>
<td>176</td>
<td>163</td>
<td></td>
</tr>
</tbody>
</table>

$^a$Soft tissue included skeletal muscle, adipose tissue, cartilage, blood, lymphatic tissues, and connective tissues. For ICRP 110 phantoms, teeth, tongue, tonsils, and ureters were all set to soft tissue for comparison with the XCAT phantoms.

$^b$Lungs were compressed in the ICRP 110 phantoms, but dilated in the XCAT reference phantoms. The densities of the lungs were set such that the total mass of the lungs match the reference lung mass.

$^c,d,e,f$These GI track organs included both wall and contents for XCAT reference phantoms but only wall for ICRP 110 reference phantoms. The ICRP89 reference values were organ walls.

$^e$Bladder included only wall.

$^h$Skeleton included cortical bone, trabecular bone, yellow marrow, red marrow, and various connective tissues.
2.2.1.2 ICRP 110 voxelized phantoms

The second set of phantoms was the reference male and female phantoms (Figures 2c and 2d) provided in ICRP publication 110. The phantoms were constructed from tomographic data of individuals whose body heights closely matched to the reference values defined in ICRP publication 89. Initially, radiosensitive organs were directly segmented from the tomographic data using commercial image processing software by applying CT number thresholding. The resulting male and female voxelized phantoms, referred to as Golem and Laura, were then modified to match the following reference body parameters: height, organ mass, and total body mass. Specifically, the voxels were scaled along the body long axis to match the reference height and then adjusted again to match the skeletal mass according to ICRP publication 70, ICRP publication 89, and ICRU report 46. Subsequently, individual organ volume was modified to match the reference mass. Finally, additional tissues and different body regions were modified to match the total reference mass. The resulting voxel sizes for the reference male phantom were 8 mm along the body long axis and 2.137 mm in the transverse plane. The respective values for the female phantom were 4.84 mm and 1.775 mm. Similar to the XCAT phantoms, the skin was also modeled as a single voxel layer on the surface, causing the skin mass to be higher than the ICRP 89 reference mass.
2.2.1.3 ImPACT stylized phantom

The third type of phantom (Figure 2e) was a stylized/mathematical phantom—the ImPACT hermaphrodite phantom—which is available commercially from the ImPACT website (ImPACT CT Patient Dosimetry Calculator, version 1.0.3; ImPACT, London, England). This phantom is composed of 208 contiguous 5 mm thick slabs extending from upper legs to head. It was first designed for a UK national survey of doses to patients from conventional X-ray examinations. Definition of individual organs and cross-section data can be found in NRPB-R186.

2.2.1.4 CT-Expo stylized phantoms

The fourth set of phantoms was stylized/mathematical phantoms (Figure 2f and 2g) based on the design characteristics of the MIRD-5 phantom. The two sex-specific adult phantoms ADAM and EVA were originally created in the German National Research Center for Environment and Health (GSF) based on reference male and female organ masses given by ICRP publication 23. The ratios of reference female to male organ masses were analyzed, yielding an average value of 0.89 and the whole body mass ratio of 0.83. As the MIRD-5 phantom had similar dimensions of the male reference adult, the female phantom was derived to a first approximation by shrinking all relevant volumes of the MIRD-5 phantom with the total whole body mass ratio of 0.83. Then, female organ masses were modified to match the reference ratios. Finally, sex-specific organs including testes, ovaries, uterus and breasts were added to the phantoms. The resulting
phantoms consisted of an elliptical cylinder for the trunk and arms, two truncated circular cones for the legs, and a circular cylinder with an elliptical cylinder capped by half an ellipsoid for the neck and head. Organ masses, total body mass and height was tabulated in Table 1.

2.2.2 CT examination categories

Body and neurological CT protocols routinely used at our institution were reviewed. Thirteen examination categories were selected for this study, consisting of 10 body categories and 3 neurological categories (Table 2). Each examination category represented a class of protocols that cover the same anatomical region and share the same scan parameters, including tube voltage, pitch, beam collimation, and the type of scan field-of-view (Table 3). These scan parameters were explicitly modeled in the Monte Carlo simulations. Before simulating a given protocol, relevant organ locations were computed along the longitudinal body axis to locate the starting and ending anatomical landmarks (Table 2). For helical scans, over-ranging (necessary for data interpolation in helical reconstruction) was added to the total scan length. For the helical scan parameters in Table 3, the total over-ranging distance (a sum of the over-ranging distances at the beginning and the end of the scan) was estimated to be 6.4 cm. This value was used for all but the CT-Expo phantoms; an over-ranging distance of 5.55 cm was automatically considered by the CT-Expo dosimetry spreadsheet.
Table 2: CT examination categories investigated in this study.

<table>
<thead>
<tr>
<th>examination categories</th>
<th>simulated image coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>start (1 cm above)</td>
</tr>
<tr>
<td>Body</td>
<td></td>
</tr>
<tr>
<td>chest-abdomen-pelvis</td>
<td>lung apex</td>
</tr>
<tr>
<td>chest</td>
<td>lung apex</td>
</tr>
<tr>
<td>abdomen-pelvis</td>
<td>superior liver</td>
</tr>
<tr>
<td>abdomen</td>
<td>superior liver</td>
</tr>
<tr>
<td>pelvis</td>
<td>superior iliac crest</td>
</tr>
<tr>
<td>adrenals</td>
<td>superior adrenals</td>
</tr>
<tr>
<td>liver</td>
<td>superior liver</td>
</tr>
<tr>
<td>kidneys</td>
<td>superior kidney</td>
</tr>
<tr>
<td>liver to kidneys</td>
<td>superior liver</td>
</tr>
<tr>
<td>kidneys to bladder</td>
<td>superior kidney</td>
</tr>
<tr>
<td>Neurological</td>
<td></td>
</tr>
<tr>
<td>head</td>
<td>scalp top</td>
</tr>
<tr>
<td>neck</td>
<td>C1</td>
</tr>
<tr>
<td>head and neck</td>
<td>scalp top</td>
</tr>
</tbody>
</table>
Table 3: Scan parameters for body and neurological examination categories.

<table>
<thead>
<tr>
<th></th>
<th>tube voltage</th>
<th>pitch</th>
<th>beam collimation</th>
<th>scan field-of-view</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body examination categories</td>
<td>120 kVp</td>
<td>1.375</td>
<td>40 mm</td>
<td>large body</td>
</tr>
<tr>
<td>Neurological examination</td>
<td>120 kVp</td>
<td>1</td>
<td>20 mm</td>
<td>head</td>
</tr>
<tr>
<td>categories</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.2.3 Organ doses simulations

2.2.3.1 XCAT and ICRP 110 phantoms

For XCAT and ICRP 110 phantoms, a Monte Carlo program previously developed in our laboratory was used to simulate organ doses (Figure 1).\textsuperscript{13} This program was based on a benchmarked Monte Carlo subroutine package (PENELOPE, version 2006, Universitat de Barcelona, Spain) specialized for photon, electron and positron transport.\textsuperscript{37, 38} This program explicitly simulates the geometry of the GE LightSpeed VCT system (GE Healthcare, Waukesha, WI), including the complex 3D bowtie filters as well as the trajectories of X-ray tube motion during axial and helical scans. The accuracy of the simulated dose was previously validated in a cylindrical phantom and two anthropomorphic phantoms in both axial and helical scanning modes. Simulations agreed with measurements to within 1-11\% on average and 5-17\% maximum.\textsuperscript{13} Arms of XCAT reference phantoms were positioned up for body examinations and down for neurological examinations; arms of ICRP 110 phantoms were set to vacuum for body examinations and remained unchanged for neurological examinations. Organ labels and densities for ICRP 110 phantoms were adapted in order to run the phantoms through the Monte Carlo simulation.

Energy deposited in organs and tissues was tallied for the dose computation.\textsuperscript{14} To estimate dose to the red bone marrow, volume-averaged photon fluence spectrum was tallied individually at each skeletal site and used to calculated dose to the red bone
marrow via fluence-to-dose conversion coefficients. A single active marrow dose was then calculated as its skeletal average using the age-dependent fractional distribution of active marrow tabulated in ICRP 89. Dose to the bone surface was approximated by the mass-weighted average of dose to the homogenous bones. Doses to organs that were not explicitly modeled were approximated by doses to neighboring organs. A total of $8 \times 10^7$ histories were simulated to achieve relative errors of less than 1% for organs inside the scan coverage.

2.2.3.2 ImPACT phantoms

For the ImPACT phantom, the ImPACT CT dosimetry spreadsheet provides organ doses based on 23 Monte Carlo data sets from National Radiological Protection Board (NRPB)'s SR250 report. The Monte Carlo techniques were initially developed at the NRPB in support of a UK national survey of doses to patients from conventional X-ray examinations. Modifications, including rotating fan beam spectral x-ray source and bow-tie shaped filter, were accommodated to the Monte Carlo program to simulate commercial CT scanners. Doses generated by this program were compared to doses from GSF Monte Carlo code using a female GSF phantom. Good agreements among doses were found between these two programs for the same input conditions.

The data set for one model of CT scanner included doses received when each of 208 contiguous 5 mm thick slabs of the hermaphrodite phantom is individually irradiated. The dose was expressed as absorbed dose in the organ relative to the dose on
the axis of rotation of the scanner in the absence of the phantom, i.e. free-in-air axial
dose. In order to use the normalized organ dose data to estimate patient dose for a
specific CT examination on a specific scanner, several steps were employed by the
spreadsheet. These steps involved obtaining scan volume, total normalized organ doses
(\(\sum V D_f\)), packing factor \((p)\), and CTDI\(_n\). Doses to organs were calculated by the
multiplication of \(\sum V D_f\), \(p\), and CTDI\(_n\). Over-ranging was also added to the total scan
region when defining the start and end position of the scan.

2.2.3.3 CT-Expo phantoms

For the CT-Expo male and female phantoms, similar to the ImPACT dosimetry
spreadsheet, the CT-Expo dosimetry spreadsheet provides organ doses. The spreadsheet
is based on computational methods for evaluating the data collected in two German
surveys on CT exposure practice in 1999 and 2002. The methods used Monte Carlo
simulation to transport radiation in the phantoms. Doses were calculated as conversion
factors \((f)\) of individual mean organ doses per axial free-in-air kerma for single slices at
positions varying contiguously from 10 cm below the bottom of the trunk up to the top
of the head with slice thickness of 1 cm. Mean organ doses can then be obtained by
summing up the values of \(f(\text{organ},z)\) over the scanned region as \(D(\text{organ}) = K_{\text{air}} \times \sum_{z_l}^{z_u} f(\text{organ},z)\), where \(z_l\) and \(z_u\) indicate the lower and upper boundaries of the
scanned region and \(K_{\text{air}}\) is the axial free-in-air kerma.
2.2.4 Effective dose and cancer risk index calculations

Effective dose was calculated from the obtained organ doses using the tissue weighting factors defined in ICRP publication 103.\(^1\) Effective dose for the ImPACT and the CT-Expo phantoms were conveniently provided by the dosimetry spreadsheets. For XCAT and ICRP 110 reference phantoms, which were run through the validated Monte Carlo simulation code, effective dose was calculated as follows. Organ doses obtained from the Monte Carlo method were first averaged over male and female for each type of phantoms. Dose to the testes or ovaries was averaged to obtain the dose to gonads. Following the recommendations of ICRP 103, dose to the remainder tissues was first calculated separately for each gender, including gender-specific reproductive organ (male: prostate; female: uterus/cervix). The results were then averaged across genders to obtain gender-averaged dose to the remainder tissues. These gender-averaged organ doses were then weighted by the tissue weighting factors and summed to obtain effective dose, as

$$ED = \sum_T w_T \frac{H_T^{Male} + H_T^{Female}}{2},$$

where \(w_T\) is the tissue weighting factor defined by ICRP publication 103 and \(H_T\) is the dose for organ \(T\). DLP was calculated as the product of volume-weighted CT dose index (CTDI\(_{vol}\)) and total scan length, where the CTDI\(_{vol}\) was obtained from the technical manual of the GE LightSpeed VCT scanner simulated in this study. After calculation of DLP for each anthropomorphic phantom, DLPs for XCAT phantoms and ICRP 110
phantoms were averaged over their male and female phantoms. Gender-averaged $k$ factor was determined by dividing the obtained effective dose over the gender-averaged DLP.

In order to estimate cancer risk, risk index (RI) was obtained as

$$RI = \sum_T r_{T(gender,age)}H_T,$$

where $r_T$ is the gender-, age-, and tissue-specific risk coefficient with the unit of cases/100,000 exposed to 0.1 Gy and $H_T$ is the equivalent dose to organ T. The values of $r_T$ were tabulated in BEIR VII report for lifetime attributable risk of cancer incidence.\(^{42}\) In this study, all phantoms were assumed to be 20 years old for a conservative risk estimation. For males, values of $r_T$ are available for leukemia and for cancers of stomach, colon, liver, lung, prostate, bladder, and thyroid. For females, values of $r_T$ are available for leukemia and for cancers of stomach, colon, liver, lung, breast, uterus, ovary, bladder, and thyroid. Cancers of other radiosensitive organs share a collective risk coefficient $r_{other}$, also provided in BEIR VII report.\(^ {42}\) $r_{other}$ was applied to a weighted average of the dose to other radiosensitive organs as described by Li et al.\(^ {14}\) For the XCAT, the ICRP 110, and the CT-Expo phantoms, risk index was calculated for each gender separately. For the ImPACT hermaphrodite phantom, since only one set of organ doses was provided for each examination category, that set of data was used to calculated risk index with different $r_T$ values for male and female. Risk index values were then normalized over their corresponding DLPs to obtain q factors (Figure 1).
2.3 Results

2.3.1 Comparison of organ doses

Figure 3 shows the organ doses estimated using the four types of phantoms for the 13 examination categories. Some organs received noticeably different doses between phantoms for the same examination. For example, in the chest-abdomen-pelvis and abdomen-pelvis examinations, doses to the testes for the XCAT and the ICRP 110 male phantoms were less than half of the doses to the testes for the ImPACT and the CT-Expo male phantoms. In the pelvis examination, doses to the testes for the ICRP 110 phantoms differed by four-fold from the XCAT phantom and even more from the ImPACT and the CT-Expo phantoms. In the abdomen-pelvis, abdomen, liver, and liver-to-kidneys examinations, dose to breasts for the ImPACT phantom was much smaller compared to doses for the other three female phantoms. Esophageal doses for the two voxelized phantoms (XCAT and ICRP 110) were smaller than the two stylized phantoms (ImPACT and CT-Expo) in the chest-abdomen-pelvis and chest examinations, but were larger in the abdomen-pelvis, abdomen, liver, and liver-to-kidneys examinations.

The quantitative differences between phantoms are summarized in Tables 4 and 5 for fully-irradiated organs (organs directly irradiated and completely within the scan coverage for all four types of phantoms) and partially-irradiated organs (organs directly irradiated in four types of phantoms and partially inside the scan coverage for at least one type of phantoms). Two comparison methods were used: comparisons across all
four types of phantoms using coefficient of variation (COV) and the difference between the ICRP 110 phantoms used as the reference standard and the other three types of phantoms. It is obvious that the average COV for fully irradiated organs were smaller than the COV for partially irradiated organs.

In general, the average differences between each type of phantoms and ICRP 110 phantoms were also smaller for fully irradiated organs than those for partially irradiated organs (Tables 4 and 5). For male phantoms, the average differences between the XCAT and the ICRP 110 phantoms (ranging from 3% to 22% for fully irradiated and 6% to 21% for partially irradiated organs) were overall smaller than those between the ImPACT and the ICRP 110 phantoms (ranging from 13% to 37% for fully irradiated and 12% to 72% for partially irradiated organs) or between the CT-Expo and the ICRP 110 phantoms (ranging from 8% to 38% for fully irradiated and 16% to 66% for partially irradiated). This trend was not demonstrated as prominently in the female phantoms. For fully irradiated female organs, the average differences between the CT-Expo and the ICRP 110 phantoms appeared to be the smallest (ranging from 3% to 20%), and the average differences between the XCAT and the ICRP 110 phantoms for partially irradiated female organs were the smallest (ranging from 8% to 56%).
Figure 3: Comparison between different types of phantoms in terms of organ doses and effective doses (ED) in 13 examination categories: (a) chest-abdomen-pelvis; (b) chest; (c) abdomen-pelvis; (d) abdomen; (e) pelvis; (f) adrenals; (g) liver; (h) kidneys; (i) liver-to-kidneys; (j) kidneys-to-bladder; (k) head; (l) neck; (m) head-and-neck. Note that doses for ImPACT are the same for male and female except for testes and ovaries. Doses are normalized to 100 mAs. The quantitative differences were tabulated in Tables 4 and 5. The coefficient of variation for ED is displayed above the bars for each examination.
Table 4: Coefficients of variation (COV) and average differences of fully irradiated organs for all 13 examination categories. The average COV was obtained by first calculating COV for each organ across four phantoms, and then averaged over all fully irradiated organs. The average difference was calculated using: $|D_{\text{XCAT}}/D_{\text{ICRP110}}-1|$, $|D_{\text{ImPACT}}/D_{\text{ICRP110}}-1|$, and $|D_{\text{CT-Expo}}/D_{\text{ICRP110}}-1|$, and then averaged over all fully irradiated organs. The CT-Expo male phantom does not have any breasts, so breasts were excluded in the calculation for male. The female only organs were bracketed in the organ list. Note that for the adrenals, kidneys, and neck examinations there was no fully radiosensitive organs.

<table>
<thead>
<tr>
<th>Fully irradiated</th>
<th>average COV across four phantoms</th>
<th>average difference between XCAT and ICRP 110</th>
<th>average difference between ImPACT and ICRP 110</th>
<th>average difference between CT-Expo and ICRP 110</th>
</tr>
</thead>
<tbody>
<tr>
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<td>male</td>
<td>female</td>
</tr>
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<td>0.13</td>
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<td>chest</td>
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<td>0.14</td>
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<td>16</td>
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<tr>
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<td>7</td>
<td>21</td>
</tr>
<tr>
<td>pelvis</td>
<td>0.22</td>
<td>0.18</td>
<td>22</td>
<td>21</td>
</tr>
<tr>
<td>adrenals</td>
<td>0.11</td>
<td>0.10</td>
<td>7</td>
<td>20</td>
</tr>
<tr>
<td>liver</td>
<td>0.11</td>
<td>0.10</td>
<td>6</td>
<td>20</td>
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<tr>
<td>kidneys</td>
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<td>10</td>
<td>16</td>
</tr>
<tr>
<td>liver to kidneys</td>
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<td>0.06</td>
<td>5</td>
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</tr>
<tr>
<td>kidneys to bladder</td>
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<td>0.09</td>
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</tr>
<tr>
<td>head and neck</td>
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<td>0.09</td>
<td>3</td>
<td>5</td>
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</tbody>
</table>
Table 5: Average differences and coefficients of variation (COV) of partially irradiated organs for all 13 examination categories.

Table 4b. Average differences and COV of partially irradiated organs for all 13 examination categories.

<table>
<thead>
<tr>
<th>Partially irradiated</th>
<th>average COV across four phantoms</th>
<th>average difference between XCAT and ICRP 110</th>
<th>average difference between ImPACT and ICRP 110</th>
<th>average difference between CT-Expo and ICRP 110</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>male</td>
<td>female</td>
<td>male</td>
<td>female</td>
</tr>
<tr>
<td>chest-abdomen-pelvis</td>
<td>0.25</td>
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<td>12</td>
<td>13</td>
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<tr>
<td>chest</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>abdomen</td>
<td>0.30</td>
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<td>kidneys</td>
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<td>head</td>
<td>0.22</td>
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<td>12</td>
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<tr>
<td>neck</td>
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<td>8</td>
</tr>
<tr>
<td>head and neck</td>
<td>0.18</td>
<td>0.19</td>
<td>11</td>
<td>14</td>
</tr>
</tbody>
</table>
2.3.2 Comparison of effective doses and risk indices

The differences between effective doses of the four types of phantoms (Figure 3) were not as dramatic as the differences in organ doses. COV of effective doses across all four types of phantoms was calculated for each examination category and displayed in Figure 3. The effective dose COV for all the examinations other than pelvis (0.21) and head (0.23) examinations, were less than 0.2, with the lowest value being 0.03 (abdomen-pelvis examination). Percent differences for effective doses using ICRP 110 phantoms as the reference standard showed that the XCAT and the ICRP 110 were very close; the percent differences between the two were under 10% for most examination categories except the head examination, which had a percent difference of 20%. In contrast, the maximum percent difference between the ImPACT and the ICRP 110 phantoms was 42% (pelvis examination) and between the CT-Expo and the ICRP 110 phantoms was 34% (pelvis examination).

Figure 4 illustrates the risk indices for the 13 examination categories with the COV of all four phantoms displayed above the bars. The COV for the male phantoms were all under 0.20 except in the pelvis (0.28) and head (0.30) examinations, indicating the risk indices agreed well across male phantoms. The COV for female phantoms were larger than for male phantoms with maximum value of 0.49 (neck examination). The risk indices also fluctuated more across examinations for females.
Figure 4: Comparison of risk index (RI) over four types of phantoms for the 13 examination categories for male (a) and female (b) phantoms. The coefficient of variation for each examination is displayed above the bars.
2.3.3 Comparison of $k$ and $q$ factors

Figure 5 and Table 6 show DLP to effective dose conversion coefficient ($k$ factor) for each examination category on all four types of phantoms. The $k$ factors for each examination agreed well across phantoms, providing that the COV were all equal to or less than 0.20, with the exception of the head examination (0.30). Average difference with respect to the ICRP 110 phantoms showed that $k$ factors from the XCAT phantoms were the closest to the ICRP 110 phantoms (average difference of 11% across 13 examination categories). The $k$ factors from the ImPACT and CT-Expo phantoms had similar average differences relative to ICRP 110 phantoms (20% for ImPACT and 21% for CT-Expo). As expected, the $k$ factors for body examinations were significantly higher than those of neurological examinations. For body examinations, $k$ factors for ICRP 110 phantoms were the largest among all four types of phantoms except for the pelvis examination. The $k$ factors from AAPM publication 96 are displayed in the same graph for reference. These values are smaller than any of the values calculated for body examinations in this study, but no apparent trend was observed for neurological examinations.

Figure 6 and Table 6 show the DLP to risk index conversion coefficient ($q$ factor) for all four types of phantoms. The $q$ factors from the four male phantoms agreed well, having COV all equal to or less than 0.20, with the exception of head examinations (0.36). For females, $q$ factors showed more variance across different types of phantoms with the
maximum COV of 0.54 from the head-and-neck examination. For both males and females, $q$ factors calculated from the XCAT and the ICRP 110 phantoms agreed well, with an average difference of 10% for males and 13% for females across all examination categories. The $q$ factors from CT-Expo phantoms had a higher percent difference from ICRP 110 phantoms, with an average difference of 17% for males and 22% for females. The $q$ factors from the ImPACT phantom had the highest percent difference from ICRP 110, with an average difference of 20% for males and 31% for females.

The $q$ factors showed drastic variation between male and female. For males, the $q$ factors were small and consistent across body examinations (COV of 0.11 across all body examinations and male phantoms), while for females, the $q$ factors showed a high degree of variability.
Figure 5: Comparison of k factor among four types of phantoms for 13 examination categories. The k factor for XCAT, ICRP 110, and CT-Expo phantoms used gender averaged effective dose and DLP. The tabulated k values for 6 protocol classes from the AAPM were also included for comparison in this graph. The coefficient of variation for each examination is displayed above the bars.
Figure 6: Comparison of q factor over four types of phantoms for the 13 examination categories for male (a) and female (b) phantoms. The coefficient of variation for each examination is displayed above the bars.
Table 6: k and q factor over three types of phantoms for the 13 examination categories.

<table>
<thead>
<tr>
<th></th>
<th>k (mSv/mGy-cm)</th>
<th>q (cases/10,000 exposed/100 mGy-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>XCAT</td>
<td>ICRP110</td>
</tr>
<tr>
<td>chest-abdomen-pelvis</td>
<td>0.018</td>
<td>0.019</td>
</tr>
<tr>
<td>chest</td>
<td>0.025</td>
<td>0.026</td>
</tr>
<tr>
<td>abdomen-pelvis</td>
<td>0.018</td>
<td>0.019</td>
</tr>
<tr>
<td>abdomen</td>
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<td>0.024</td>
</tr>
<tr>
<td>pelvis</td>
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<td>0.012</td>
</tr>
<tr>
<td>adrenals</td>
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<td>0.029</td>
</tr>
<tr>
<td>liver</td>
<td>0.026</td>
<td>0.029</td>
</tr>
<tr>
<td>kidneys</td>
<td>0.020</td>
<td>0.024</td>
</tr>
<tr>
<td>liver to kidneys</td>
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<td>0.027</td>
</tr>
<tr>
<td>kidneys to bladder</td>
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<td>head</td>
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<tr>
<td>neck</td>
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<td>0.0054</td>
</tr>
<tr>
<td>head and neck</td>
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</table>
Table 7: Comparison of $k$ factors obtained using ImPACT and CT-Expo phantoms in this study and from other 3 research groups. All the $k$ factors here were calculated using ICRP 103 tissue weighting factors.

<table>
<thead>
<tr>
<th>scan region</th>
<th>DLP to ED conversion coefficient - $k$ (mSv/mGy-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ImPACT from this study</td>
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<tr>
<td>head</td>
<td>0.0030</td>
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<tr>
<td>neck</td>
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<tr>
<td>chest</td>
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</tr>
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<td>abdomen</td>
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<tr>
<td>pelvis</td>
<td>0.0133</td>
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<tr>
<td>abdomen &amp; pelvis</td>
<td>0.0161</td>
</tr>
<tr>
<td>liver</td>
<td>0.0206</td>
</tr>
</tbody>
</table>
2.4 Discussion

In this study, we compared organ doses, effective doses, risk indices, k factors, and q factors across four types of phantoms. Several comparison studies between voxelized phantoms and stylized phantoms in CT have been conducted by two other research groups.10, 11, 15 These studies were focused on only one type of voxelized phantom and only examined a small number of protocols. In this study, two types of voxelized phantoms were studied, the voxelized version of the hybrid XCAT reference phantoms and the voxelized ICRP 110 reference phantoms. Monte Carlo simulated organ doses were compared for 13 routinely used body and neurological CT examination categories. DLP to effective dose conversion coefficient (k factor) was reported for each category to expand on the limited amount of published data available for various anatomical regions. Recognizing the limitations of the effective dose,43-45 we further estimated cancer risk using the risk index concept14, 36 and calculated DLP-to-risk index conversion coefficient (q factor).

Our study showed that sizable differences in organ dose exist among different types of reference phantoms despite their closely-matched organ masses, total body weight, and height. One major cause of the organ dose differences is the difference in organ locations. For example, the locations of testes in the two stylized male phantoms (ImPACT and CT-Expo) are superior to the corresponding locations in the two voxelized male phantoms (XCAT and ICRP 110). In the chest-abdomen-pelvis and abdomen-pelvis
examinations, where the scans both end at 1 cm below inferior ischium, testes in the four male phantoms were irradiated differently. The percentages of the testes length that were irradiated for the ImPACT, the CT-Expo, the XCAT, and the ICRP 110 male phantoms were 100%, 82%, 47%, and 0% respectively. This resulted in the dose to the testes being highest for ImPACT, second highest for CT-Expo, third highest for XCAT, and minimal for ICRP 110. Another example is the colon. In the XCAT female phantom, the transverse colon was superior in the body in comparison to the location of the transverse colon in the ICRP 110 female phantom. Therefore, during the chest examination, part of the colon was irradiated in the XCAT phantom, while the colon in the ICRP 110 phantom was completely outside of the scan field. This resulted in an 18-fold difference in colon dose.

In addition to organ location, the spatial distribution (the spread) of an organ also plays an important role. The breasts of the ImPACT hermaphrodite phantom have a length of 4.1 cm, which is much shorter than the female breasts in the XCAT (15.2 cm), the ICRP 110 (13.6 cm) and the CT-Expo (11.6 cm) phantoms. While the breasts were out of the scan coverage for abdomen-pelvis, abdomen, liver, and liver-to-kidneys examinations on the ImPACT hermaphrodite phantom, they were fully irradiated on the ICRP 110 female phantom and partially irradiated on the XCAT and the CT-Expo female phantoms for these examinations. This caused the breast dose in the ImPACT phantom to be much lower than in the other three female phantoms.
Because no phantoms have all the radiosensitive organs, approximation methods had to be used, which also resulted in organ dose differences between phantoms. For example, in the ImPACT and the CT-Expo phantoms, dose to the esophagus was approximated by dose to the thymus, which was much shorter than a real esophagus, causing the esophageal dose in the stylized phantoms to be very different from that in the voxelized phantoms. Thus, in the stylized phantoms, dose to esophagus was high for upper body examinations where thymus was fully irradiated, as in chest and chest-abdomen-pelvis exams, but really low for other examinations compared to the voxelized phantoms. Another example of this effect is the salivary glands. For the Impact phantom, dose to the salivary glands was approximated by dose to the brain, while for the XCAT and the ICRP 110 phantoms it was approximated by dose to the larynx-pharynx. In the head examination, the brain was fully irradiated, but the larynx-pharynx was partially irradiated. Therefore, dose to the salivary glands in the ImPACT phantom was much higher than those in the XCAT or the ICRP 110 phantoms. The location of the larynx-pharynx in XCAT phantoms are greatly inferior to that of the ICRP 110 phantoms, resulting in even smaller dose in the XCAT phantoms. The opposite trend was found in the neck examination, where the brain was out of the scan coverage and the larynx-pharynx was mostly within the scan coverage.

As mentioned earlier (section II.A), the organ masses in the XCAT reference, the ICRP 110 reference, and the ImPACT reference phantoms in this study were matched to
the organ masses recommended in the ICRP publication 89; the organ masses in the CT-Expo reference phantoms were matched to the ICRP publication 23. Nevertheless, the masses of the organs (Table 1) were very similar for all four types of phantoms, but the organ doses received can be considerably different. This indicated that the anatomical locations and spatial distributions of organs in a phantom affected radiation dose much more than the masses of the organs.

When comparing phantoms using ICRP 110 phantoms as the reference standard, XCAT male was the closest match to ICRP 110 male for both fully and partially irradiated organs. For female, XCAT was not the closest match to the ICRP 110 female for fully irradiated organs. Average diameters for the XCAT and the ICRP 110 phantoms were calculated for chest and abdomen using the following method. The body volume was first calculated by multiplying the voxel volume by the total number of voxels for chest and abdomen. The total volume was then divided by the z-axis length of each part to obtain the average axial plane area. This area was used to calculate the average diameters for chest and abdomen assuming the axial plane to be a circle. The average diameters for the XCAT female phantom are 29.32 cm for chest and 27.54 cm for abdomen, while for ICRP 110 these values are 27.1 cm and 25.75 cm respectively. The average diameters for the XCAT female are 2.22 cm and 1.79 cm larger than the diameters for the ICRP 110 female. The larger diameter in the XCAT female was partially due to single voxel layer skin. Both phantoms used one single voxel layer skin,
but the transverse plane voxel size for the XCAT female (3.45 mm) was slightly larger than the voxel size for the ICRP 110 female (1.775 mm). The average diameter difference caused major radiosensitive organs in the chest and abdomen regions (lungs, stomach, and liver) to receive less doses in the XCAT female phantom when these organs were fully irradiated. The effect of body diameters on radiation dose has been explored in the literature.\textsuperscript{16,36}

The variability in effective doses of the four types of phantoms (Figure 3) was not as dramatic as the variability in organ doses because effective dose was weighted and summed over all radiosensitive organs. The organs which received small doses tended to show higher differences in dose between phantoms, but were not as important in the summation. The same argument can be applied to risk indices for males. However, risk indices for females varied considerably across phantoms due to the large variance of lung and breast doses, which were the two highest risk organs for females.

In a clinical environment, estimating effective dose using Monte Carlo simulation is not practical. An easy and fast way to estimate effective dose is to use DLP to effective dose conversion coefficients, also known as $k$ factors. The accuracy of $k$ factors is therefore very important. In this study, we examined how $k$ factors would vary when obtained from different types of phantoms, and compared our results with the commonly used $k$ factors published in AAPM 96.\textsuperscript{46} The AAPM values were only available for a small number of examinations, which did not include some routinely
used CT examinations that were incorporated in this study. We showed that the $k$ factors for the unreported scan regions were rather different from the body regions reported in AAPM 96. Take the ICRP 110 phantoms for example, the $k$ factor of the adrenal examination is 0.0294 mSv/mGy-cm, about 1.5 times the value of chest-abdomen-pelvis examination. The result is that the effective dose calculated using the chest-abdomen-pelvis examination $k$ factor represents a gross underestimation. Therefore, the $k$ factor reported here is of great utility for clinical effective dose estimation. The $k$ factor for each examination agreed well across phantoms, which can be explained using the same argument as effective dose. For the head examination, the COV for $k$ factors was much higher than any other examination. This was due to the significant difference in doses to the salivary glands, mentioned earlier in this section.

Note that the $k$ factors in this study were all calculated using the tissue weighting factors from the ICRP publication 103, while the commonly used $k$ factors in AAPM 96 were calculated based on weighting factors from the ICRP publication 60. The $k$ factors from AAPM 96 were smaller than the corresponding $k$ factors calculated with the four types of reference phantoms for all examinations and the head-and-neck examination. In contrast, the $k$ factor for the neck examination published in AAPM 96 report is larger than any of the $k$ factors obtained in this study. Given the sizable differences, the published $k$ factors should be updated to reflect the new tissue weighting factors.
The effect of new tissue weighting factors on conversion coefficients has also been reported by other researchers.\textsuperscript{47-49} Table 7 shows the results from three other groups and compares this data with the data from the ImPACT and the CT-Expo phantoms. These two types of phantoms were chosen because the three groups all used stylized phantoms in their studies. Since the same phantom and software were used, the results from Huda \textit{et al}\textsuperscript{49} and Christner \textit{et al}\textsuperscript{47} were very similar to the data from the ImPACT phantom in this study. The only examination that showed a noticeable difference was the head exam. The inconsistency was caused by a variation in scan region. The data from Deak \textit{et al}\textsuperscript{48} showed more variance than other groups’ but closer match to the data from the CT-Expo phantoms in this study. This was expected because the CT-Expo phantoms were derived from the ORNL phantoms which were used in Deak \textit{et al}’s study. However, the two set of data still differed considerably because of the differences in scan length, anatomic variations, and Monte Carlo codes implemented in computer simulation.

Since the effective dose is based on tissue weighting factors that have been calculated from an extremely broad pool of data,\textsuperscript{41} it is not appropriate to use this concept on patients with specific age and gender. The effective dose provides dosimetry information on radiobiological risk associated detriment, but it is meant to be used in a general sense. In order to gain better understanding of dose received by different genders, the risk index was calculated for male and female separately in this study. The
\( q \) factors for each examination agreed well across male phantoms. The \( q \) factors were also consistent across body examinations with the COV of 0.11 across all body examinations, indicating the possibility of using one \( q \) factor for all male body examinations.\(^{12}\) The female \( q \) factors have a high degree of fluctuation across various phantoms and examinations for several reasons. The primary reason is the high risk of lung and breast cancer incidences. For female abdomen, liver and liver-to-kidneys examinations, the \( q \) factors of the ImPACT and the CT-EXPO phantoms were much smaller than \( q \) factors obtained from the other two phantoms. This can be explained by the relatively small dose to the breasts in the two stylized phantoms. Although gender specific effective dose has been proposed, the real gender difference cannot be represented by the effective dose unless the gender specific tissue weighting factors are used.

One limitation of this study was that only one CT scanner model was explored. The dose values for other scanners may be different from what we obtained here. However, when normalized to CTDI and DLP, doses from various scanner models show similar results.\(^{16}\) Furthermore, the major finding, i.e., organ dose differences across reference phantoms were mainly introduced by the locations, spatial distributions, and dose approximation methods, should still be applicable to other scanners. Additionally, the risk data used in the cancer risk is based on studies of atomic bomb survivors and other limited research studies involving occupational exposures, and thus suffers from large uncertainty. Finally, this study only addressed \( k \) and \( q \) factors across reference size
adult phantoms. The effect of patient size requires a presentation of its own. Again, the main purpose of this study was to provide insight into the effects that different types of reference phantoms have on CT dosimetry, and thus lead to a better understanding of radiation dose received by patients undergoing CT examinations.

### 2.5 Conclusion

In this study, the XCAT reference male and female, the ICRP 110 reference male and female, the ImPACT reference hermaphrodite, and the CT-Expo reference male and female phantoms were compared for CT dosimetry. Dose differences for fully irradiated radiosensitive organs were much smaller than those for partially irradiated organs. The observed differences were mainly introduced by variation in organ location (e.g. testes in the pelvis examination; colon in the female chest examinations), spatial distribution (e.g. female breasts in abdomen-pelvis, abdomen, liver, and liver-to-kidneys examinations), as well as the approximation method implemented (e.g. esophagus in chest and chest-abdomen-pelvis examinations; salivary glands in head and neck examinations). The weighted dosimetry quantities including effective doses, male risk indices, \( k \) factors, and male \( q \) factors agreed well across phantoms, because organs which received small doses tended to show higher variation in dose between phantoms, but were not as important in the summation. The female risk indices varied considerably across phantoms due to high risk of lung and breast cancer incidence.
3. Comparison of patient specific dose metrics between chest radiography, tomosynthesis, and CT for adult patients of wide ranging body habitus

3.1 Introduction

There are three main x-ray based modalities for imaging the thorax: radiography, tomosynthesis, and CT. Chest radiography remains the most commonly performed diagnostic imaging test overall, especially for the diagnosis of many pulmonary diseases. The advantages of chest radiography include high accessibility, low cost and minimal radiation dose to lungs and breasts. However, the detectability of pathologies in radiography is very limited by quantum noise, spatial resolution, and overlaying projected anatomy. The introduction of computed tomography (CT) in the 1970’s has provided a great solution for limitations of the overlaying anatomy in radiography to image the inner depth of the body, slice by slice. The high level of feature resolution in CT brings with it much higher radiation exposure to the public, which has increased concern about CT imaging among health care professionals. Tomosynthesis, which can also eliminate overlaying structures and provide depth information, was introduced to the medical imaging world as a possible low dose alternative to CT. It is certain that each of the three imaging modalities carries its own value and is beneficial to patients, but the ratio of benefit to radiation risk should be well assessed before deciding on the

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1 This chapter is based on a manuscript with the same title submitted to the journal Medical Physics
appropriate modality to implement. Therefore, it is important to have the ability to accurately estimate radiation doses that patients receive during these procedures to place them in perspective with diagnostic quantity.

There are many radiation dose studies focused on a specific procedure\textsuperscript{55-65} as well as several studies comparing radiation doses between the three chest imaging modalities.\textsuperscript{66, 67} Both Sabol and Bath’s study simulated the chest radiography and tomosynthesis, however, previous comparison studies across the three modalities have not been based on one common platform.\textsuperscript{66, 67} Limited to one generic phantom, patient specific doses have not been previously compared.

This study fills this gap by estimating organ doses, effective doses and risk indices for each of the three modalities. This study used a common Monte Carlo simulation platform to enable direct comparison of the results. Furthermore, this study was based on 59 voxelized phantoms emulating patient variability that exists in a clinical practice. As such, this study aimed to offer a comparison of the three modalities using patient specific methods.

3.2 Methods

3.2.1 Patients and XCAT Computational Phantoms

A total of 59 adult patients (35 male and 24 female) were studied. These patients were chosen retrospectively from our CT data such that they represent a wide range of body types and ages of adult males and females. Their BMIs ranged from 19.20 kg/m\textsuperscript{2} to
36.11 kg/m$^2$ for male and from 18.21 kg/m$^2$ to 38.81 kg/m$^2$ for female; their ages ranged from 18 to 78 for male and from 27 to 75 for female. An experienced radiologist examined the chest-abdomen-pelvis (CAP) CT data of these patients and ensured that their anatomies were normal. The CAP data were then used in the first step of phantom building, as outlined below.$^{24,68}$

These computational phantoms were created at Duke RAI Laboratories based on a four step process.$^{68}$ First, high resolution chest-abdomen-pelvis CT data were collected such that the chosen patients followed a good BMI distribution. These CT data were then segmented semi-manually by in-house software ImageSegment (RAI Laboratories, Duke University, Durham, NC) on a tablet. Second, the obtained segmentation data were imported to a processing software (Rhinoceros, [www.rhino3d.com](http://www.rhino3d.com)) to build 3D NURBS models. The surfaces of segmented organs were smoothed and fit to 3D polygon mesh surfaces. After the trunk was built, the length of arms and legs were determined according to a linear relationship between trunk height and body height, and then attached to the trunk. Third, the large deformation diffeomorphic metric mapping (LDDMM) was applied to obtain the patient’s framework.$^{69}$ Lastly, the transformed phantom was finalized by careful virtual examination. All the phantoms were isotropically voxelized with 3.45 mm voxels for the implementation of Monte Carlo simulations. During the CT simulation, patients were “positioned” on a table to mimic the real clinical setting (Figure 13b).
Among all the phantoms, one male and one female phantoms’ organ weights were adjusted to match the reference values published in ICRP 89. Thus, they are named reference phantoms in the XCAT phantom family.

![Figure 7: Schematic illustration of the tomosynthesis acquisition geometry (a) and the CT acquisition geometry (b).](image)

### 3.2.2 Organ dose simulation

The Monte Carlo simulation software PENELOPE (version 2006, Universitat de Barcelona, Spain) was used to calculate the organ dose for all modalities. Energy deposition in organs and tissues was tallied for each modality and used later for the dose computation. A total of $8 \times 10^7$ histories were simulated for each examination to achieve relative errors of less than 1% for organs inside the field-of-view.

#### 3.2.2.1 Chest x-ray radiography configuration

A clinical radiography system with the capability of conducting chest radiography and tomosynthesis (Definium 8000, GE Healthcare) was modeled. To accurately generate the x-ray spectrum, the half-value-layer (HVL) was measured to be 6.9 mm Al at the chest x-ray clinical setting (120 kVp with 2 mm Al + 0.1 mm Cu
filtration). xSpect software was then used to generate the spectrum that yielded the same HVL.\textsuperscript{70}

Since the radiation dose is not affected by the lateral direction field-of-view (FOV) if the radiation field can cover the body in that direction, the largest detector FOV (41 cm) was chosen for chest posteroanterior, anteroposterior, and tomosynthesis examinations and a 35 cm FOV was chosen for the left lateral examination. To determine the vertical collimation, the longitudinal locations of the apex and bottom of the lungs were first computed. Two 3 cm margins were added above the apex and below the bottom to approximate the clinical setting (Table 8). The x-ray source was located on the same plane as the central transaxial plane of the lungs.

3.2.2.2 Tomosynthesis configuration

The radiographic system modeled in this study is enabled to conduct tomosynthesis sweeps by installing the VolumeRAD software. This software controls the x-ray tube head movement in the vertical direction and performs step and shoot procedures to obtain tomosynthesis projections. The configuration of this system is shown in Figure 13a. The extreme angles with respect to the horizontal direction were -15.3° and +15.2° with a pivot-point-to-image-distance of 9.9 cm. In the real clinical setting, 60 projections are taken during one sweep with the same vertical increment between the extreme angles. The high number of projection angles is needed for reconstruction; for the dosimetry purpose of this study, 20 angles were used considering that radiation dose
difference between adjacent angles is extremely small. In this study, collimation of the beam remained the same for all angles. The effect of the unchanged collimations will be discussed later.

3.2.2.3 Radiographic and tomosynthesis techniques

To calculate the radiation dose, mAs values are required. The Duke CIPG (Clinical Imaging Physics Group, Duke University, Durham, NC) technique charts were employed to determine the mAs technique for the chest posteroanterior, anteroposterior and left lateral examinations shown in Table 8. For tomosynthesis, the total mAs was ten times that of the corresponding posteroanterior mAs, which was then equally distributed between the 20 angles (Table 8).
Table 8: Imaging techniques for all modalities. PA = Posteroanterior. AP = Anteroposterior. LAT = Lateral.

<table>
<thead>
<tr>
<th>Examination</th>
<th>Modalities</th>
<th>PA and AP</th>
<th>Left LAT</th>
<th>Tomosynthesis</th>
<th>CT</th>
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<tbody>
<tr>
<td>mAs or CTDI&lt;br&gt;vol</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>(cm)</td>
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<td>mAs</td>
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</tr>
<tr>
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<td>&gt; 39</td>
<td>7.6</td>
<td>&gt; 27</td>
<td>31</td>
</tr>
</tbody>
</table>

Scan mode - - - - Helical
Pitch - - - - 1.375
Beam collimation - - - - 40 mm
Scan field-of-view - - - - Large body
Tube voltage 120 kVp 120 kVp 120 kVp 120 kVp
Scan coverage 3 cm margins above and below lungs 1 cm margins above and below lungs

3.2.2.4 CT system simulation and scan techniques

A Monte Carlo dose program previously developed in our laboratory was used for chest CT dose calculation.\textsuperscript{71, 72} The Monte Carlo program modeled the different components of a 64-slice CT system (LightSpeed VCT, GE Healthcare). The accuracy of the dose simulated by this program was validated in a cylindrical phantom and two anthropomorphic phantoms for both axial and helical scanning modes. Simulations were found to agree with measurements within 1-11% on average and 5-17% maximum.\textsuperscript{71}

The Monte Carlo program calculates energy deposition to organs and tissues per unit CTDI<br>vol values. The CTDI<br>vol values for a chest CT examination on the GE VCT
machine was studied in our group. It was found that CTDI<sub>vol</sub> followed an exponential relationship (Table 8) with the patient’s diameter obtained from the scout images. This diameter was determined by taking the square root of the antetoposterior and lateral thickness of the middle part of the trunk. To employ this method, each phantom’s antetoposterior and lateral thickness was calculated and used to calculate the diameter.

### 3.2.3 Effective dose and risk index calculation

Organ dose obtained from the Monte Carlo simulation was used to calculate the effective dose defined in ICRP publication 103. Since each phantom has only one type of gender reproductive organs, dose to gonads was approximated by dose to testes or ovaries; dose to prostate or uterus/cervix was used in the calculation of dose to remainder tissues. To estimate cancer risk, risk index was calculated as

\[
RI = \sum_T r_{T(gender,age)} H_T,
\]

where \( r_T \) is the gender, age- and tissue specific risk coefficient (cases/100,000 exposed to 0.1 Gy) and \( H_T \) is the equivalent dose to organ \( T \). The tabulated lifetime attributable risk of cancer in BEIRVII report were used for the values of \( r_T \) at discrete ages with linear interpolation for intermediate ages.

### 3.2.4 Data analysis

To examine the effect of patient size on organ and effective dose and to make the result applicable to different imaging techniques, the effective dose per mAs (for chest posteroanterior, anteroposterior, left lateral, and tomosynthesis) or 100 mAs (for chest
CT) was plotted against patient thickness or diameter depending on the corresponding technique for that modality. Organ dose per mAs or 100 mAs was plotted against average chest diameter, defined as the square root of anteroposterior and lateral thickness at the beam center, so that the normalized organ dose can be easily compared with one parameter for the same patient across all modalities. Chest posteroanterior and left lateral examinations were also combined for the plots of normalized organ dose to simulate the conventional two-view chest x-ray. A nonlinear regression analysis was then performed to explore the relationship between organ or effective dose with body size.

### 3.3 Results

#### 3.3.1 Average effective dose across imaging modalities

Figure 8 shows the average effective dose of the 59 patients from each modality. The chest CT had the largest average effective dose of 3.2 mSv, while the chest posteroanterior examination had the smallest average effective dose of 0.04 mSv, which is 1.3% that of the chest CT. The average effective dose of the chest anteroposterior examination was around two times that of the chest posteroanterior examination; the average effective dose of the chest left lateral examination was around 2.5 times that of the chest posteroanterior examination. The chest tomosynthesis had the highest average effective dose among radiographic examinations, which was about ten times that of the chest posteroanterior examination but still only about 12% that of the chest CT. For all
chest radiographic examinations, the coefficient of variation of the average effective dose ranged from 10% (posteroanterior examination) to 19% (left lateral examination), while for CT it is much higher at 35%.

![Graph showing average effective dose across imaging modalities. ED = Effective dose. PA = Posteroanterior. AP = Anteroposterior. LAT = Lateral.]

**Figure 8**: Average effective dose across imaging modalities. ED = Effective dose. PA = Posteroanterior. AP = Anteroposterior. LAT = Lateral.

### 3.3.2 Effect of patient size on radiation dose metrics

Figures 9 show the distribution of effective dose for all patients. With increasing patient average chest diameter, the effective dose for CT increased considerably in an exponential fashion, while effective dose for radiographic modalities only increased slightly. The ratio of effective dose for chest CT versus tomosynthesis showed a
significant slope as a function of chest diameter, while that ratio for chest tomosynthesis versus the two-view chest x-ray remained rather flat.

![Figure 9](image_url)

**Figure 9:** (a) Distribution of effective dose with respect to patient size for all modalities; (b) effective dose ratio between chest CT and tomosynthesis and between chest tomosynthesis and conventional two-view chest x-ray. Average chest diameter is defined as the square root of anteroposterior multiplying lateral thickness at the beam center. ED = Effective dose. PA = Posteroanterior. AP = Anteroposterior. LAT = Lateral.

Figures 10 show the distribution of risk index for all patients. When plotting risk index versus chest diameter, all patients were set to 40 years old to eliminate the effect of age. Risk index values across the four modalities and the corresponding risk index ratio showed similar trends as effective dose for both female and male patients. For the same size female and male patients, risk index for females was about twice that of males. The risk index ratios for males and females showed similar results.
Figure 10: (a) & (c) Distribution of risk index with respect to patient size for all modalities; (b) & (d) risk index ratio between chest CT and tomosynthesis and between chest tomosynthesis and conventional two-view chest x-ray. Average chest diameter is defined as the square root of anteroposterior multiplying lateral thickness at the beam center. ED = Effective dose. RI = Risk index. PA = Posteroanterior. AP = Anteroposterior. LAT = Lateral.

3.3.3 Correlation of patient size with effective dose per mAs or 100 mAs

Figures 11 depict the exponential relationship between effective dose per mAs or 100 mAs with body size. Table 9 tabulates the fitting parameters for the following formula:

$$ ED = \exp (\alpha_{EDD} + \beta_{ED}) $$
where $d$ is the body dimension related to the technique used for that protocol. For the chest posteroanterior, anteroposterior, and tomosynthesis examinations, $d$ was the anteroposterior thickness at the beam center; for the left lateral examination, $d$ was the lateral thickness at the beam center; for chest CT, $d$ was the square root of the average anteroposterior and lateral thicknesses for the central part of trunk. Chest tomosynthesis had the highest $R^2$ value indicating the best correlation between effective dose per mAs and anteroposterior thickness, which can also be observed in Figure 11c. To the contrary, the chest anteroposterior examination had the smallest $R^2$ value, which can be observed by the wide spread points in Figure 11a. The chest posteroanterior and tomosynthesis examinations had a very similar distribution of effective dose per mAs, thus close $\alpha_{ED}$ and $\beta_{ED}$ values.
Figure 11: Effective dose per mAs or 100 mAs as a function of body dimension for all patients and modalities: (a) Chest PA and Chest AP; (c) Chest left lateral (Left LAT); (d) Chest tomosynthesis; (e) Chest CT. For (a), (b), and (c), patient’s anteroposterior thickness at the beam center is used for the x-axis; for (c), patient’s lateral thickness at the beam center is used for the x-axis; for (e), average diameter is used for the x-axis. “+” or “x” are the effective dose values calculated from the organ dose of individual patients. Lines are the exponential fit $ED (d) = \exp (\alpha_{ED} + \beta_{ED})$ with parameters $\alpha_{ED}$ and $\beta_{ED}$ tabulated in Table 9. $ED =$ Effective dose. PA = Posteroanterior. AP = Anteroposterior. LAT = Lateral.
Table 9: Exponential relationship between effective dose and body size.

<table>
<thead>
<tr>
<th>Protocol</th>
<th>$\alpha_{ED}$ (cm$^{-1}$)</th>
<th>$\beta_{ED}$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA</td>
<td>-0.047</td>
<td>-2.84</td>
<td>0.731</td>
</tr>
<tr>
<td>AP</td>
<td>-0.021</td>
<td>-2.79</td>
<td>0.256</td>
</tr>
<tr>
<td>Left LAT</td>
<td>-0.025</td>
<td>-3.10</td>
<td>0.373</td>
</tr>
<tr>
<td>Tomosynthesis</td>
<td>-0.048</td>
<td>-2.86</td>
<td>0.738</td>
</tr>
<tr>
<td>CT</td>
<td>-0.041</td>
<td>2.57</td>
<td>0.574</td>
</tr>
</tbody>
</table>

3.3.4 Correlation of patient size with organ dose per mAs or 100 mAs

Figures 12 show relationship between three large organs of interest in chest examinations with average chest diameter, defined as the square root of anteroposterior thickness multiplying lateral thickness both at the beam center. Results from the posteroanterior and left lateral study (PA + Left LAT) were combined in the plots to show the total organ dose during a conventional two-view chest x-ray. The lungs received higher dose compared to the liver and breasts in the two-view chest x-ray and tomosynthesis. The breasts received higher dose in the chest anteroposterior examination for most patients. The liver received lower dose in CT compared to that of the lungs and breasts. Table 10 tabulates the fitting parameters of the exponential relationship:

$$\text{Organ Dose} = \exp (\alpha_{\text{organ}}d + \beta_{\text{organ}}),$$

with $d$ the average chest diameter. Among all the modalities, chest tomosynthesis had the best exponential fit for organ dose and body size. Lung dose had the highest $R^2$ value, indicating best fit, which can also be observed from the plots. Dose to the breasts
showed an exponential decrease with body size for chest tomosynthesis; dose to the breasts had much weaker exponential correlation for CT and the two-view chest x-ray and even less correlation for the chest anteroposterior examination.

Figure 12: Lungs, breasts, and liver doses as a function of body dimension. Lines are the exponential fit: Organ dose \( d = \exp (\alpha_{\text{organ}} + \beta_{\text{organ}}) \) with the fitting parameters tabulated in Table 10 for each organ. Average chest diameter is defined as the square root of anteroposterior multiplying lateral thickness at the beam center. PA = Posteroanterior. AP = Anteroposterior. LAT = Lateral.
Table 10: Exponential relationship of organ dose with body size.

<table>
<thead>
<tr>
<th>Organ</th>
<th>Protocol</th>
<th>$\alpha_{\text{organ}}$ (cm$^{-1}$)</th>
<th>$\beta_{\text{organ}}$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lungs</td>
<td>AP</td>
<td>-0.039</td>
<td>-1.82</td>
<td>0.471</td>
</tr>
<tr>
<td></td>
<td>PA + Left LAT</td>
<td>-0.037</td>
<td>-1.36</td>
<td>0.590</td>
</tr>
<tr>
<td></td>
<td>Tomosynthesis</td>
<td>-0.035</td>
<td>-2.01</td>
<td>0.596</td>
</tr>
<tr>
<td></td>
<td>CT</td>
<td>-0.056</td>
<td>3.67</td>
<td>0.602</td>
</tr>
<tr>
<td>Breasts</td>
<td>AP</td>
<td>-0.008</td>
<td>-2.26</td>
<td>0.008</td>
</tr>
<tr>
<td></td>
<td>PA + Left LAT</td>
<td>-0.022</td>
<td>-2.17</td>
<td>0.201</td>
</tr>
<tr>
<td></td>
<td>Tomosynthesis</td>
<td>-0.096</td>
<td>-1.65</td>
<td>0.613</td>
</tr>
<tr>
<td></td>
<td>CT</td>
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<tr>
<td>Liver</td>
<td>AP</td>
<td>-0.060</td>
<td>-1.39</td>
<td>0.616</td>
</tr>
<tr>
<td></td>
<td>PA + Left LAT</td>
<td>-0.052</td>
<td>-1.86</td>
<td>0.509</td>
</tr>
<tr>
<td></td>
<td>Tomosynthesis</td>
<td>-0.048</td>
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<tr>
<td></td>
<td>CT</td>
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<td>3.47</td>
<td>0.403</td>
</tr>
</tbody>
</table>

3.3.5 Effect of tomosynthesis angles on radiation dose

Figures 13 show the effect of projection angles on radiation dose in chest tomosynthesis for the reference phantoms. Effective dose increased as the x-ray tube moved towards the center, maximized at approximately zero degrees, and decreased as the tube moved off-center. The difference between the minimum effective dose at angle -15.3$^\circ$ and the maximum at angle -0.9$^\circ$ was extremely small, only 0.002mSv. Dose received by the lungs, breasts, and liver for the male and female reference phantoms illustrated a very similar trend, therefore only female data is shown here. Dose to the lungs and breasts with respect to angles showed a similar trend as effective dose, with dose to the
breasts being much smaller (about one-fifth that of lungs). Dose to the liver continued increasing as the x-ray tube moved up and had a small decrease at the end.

Figure 13: (a) Effective dose at each acquisition angle of chest tomosynthesis for the reference phantoms; (b) Doses to lungs, breasts, and liver at each acquisition angle for the reference female phantom. The effective dose was averaged across male and female reference phantoms as defined in ICRP publication 103. Doses to the three organs for both reference phantoms showed the same pattern, so only female data was plotted here. ED = Effective dose.

3.4 Discussion

Organ doses, effective doses, and risk indices between the three main x-ray based chest imaging modalities (chest radiograph, tomosynthesis, and CT) were studied across 59 anatomically variable adult patients. Among these three modalities, CT perhaps provides the highest level of feature resolution but with a notably higher radiation dose. To implement the ALARA (as low as reasonable achievable) principle in making an appropriate choice between standard chest projection imaging, tomosynthesis, and CT to achieve the lowest possible dose to patients, the organ doses, effective doses, and risk indices for each modality should be accurately known. Although some comparison
studies across the three modalities have been conducted,\textsuperscript{66,67} these studies were either based on different platforms or used only one generic phantom. To the authors’ knowledge, this study was the first study that provided a dosimetric comparison across these modalities on one platform with a wide range of patient sizes.

### 3.4.1 Effective dose across imaging modalities

The average effective doses for the chest posteroanterior and left lateral study were found to be 0.039 mSv and 0.095 mSv, both of which were about twice the values reported by Sabol for the same machine and technical settings.\textsuperscript{67} There are multiple possible reasons for this as follows. First, the phantoms used in the two studies were very different. Sabol used one mathematical phantom that was scaled to a medium American male, while we used 59 voxelized phantoms that were created from real patients’ CT data. However, an earlier study comparing the effect of different types of phantoms on radiation dosimetry showed that although dose to individual organs varied considerably across phantoms, weighted dosimetry quantities such as effective dose agreed well.\textsuperscript{65} Thus, choice of phantoms should not be the major source of the difference. Second, different Monte Carlo software was used (PCXMC for Sabol’s study; PENELOE for this study). Since both studies ensured a statistical error of less than 1% during the simulation, this also should not have caused a two-fold discrepancy. Third, neither this study nor Sabol’s study validated the spectrum used in the simulation. Sabol assumed an equivalent filtration of 2.7 mm Al at 71 kVp provided by the manufacturer.
for the spectrum generated at 120 kVp. It is known that material’s linear attenuation changes with kVp, thus the equivalent filtration will be different at 120 kVp. The spectrum in our study was generated by xSpect software with its HVL matched to the measured value (Section II.B.1) at 120 kVp, which were significantly different from Sabol’s. This difference in spectrum was believed to be one of the main causes of the discrepancy in effective dose. Furthermore, mAs techniques used in the two studies were different. Sabol used 1.9 mAs for posteroanterior and 5.9 mAs for left lateral, while we used mAs adjusted values based on the patient’s body dimensions.

A mAs ratio of 10:1 was assumed for the chest tomosynthesis to the posteroanterior examination during the calculation. If a simple scale of ten was used to estimate the average effective dose of the chest tomosynthesis from the chest posteroanterior examination, it would result in a discrepancy of 3.6%, which is consistent with the findings in Svalkvist et al’s work of 3.6% but differed from Sabol’s work (discrepancy of 25%). Similar reasons can be argued for the difference between this paper and Sabol’s study.

### 3.4.2 Effect of body size on radiation dose

Exponentially decreasing effective dose per mAs or 100 mAs with increasing body size was observed as expected, agreeing with many other studies, which was simply due to the exponential absorption of x-ray photon energy by body tissues. Correlation of effective dose per mAs with body dimensions for the chest
anteroposterior and left lateral study was weaker than that of the posteroanterior and tomosynthesis studies (Figures 3a, 3b, 3c, and 3d). This can be explained by the widespread dose to the surface organ—breasts—in these two examinations (Figures 11a and 5b), which are important in chest examinations because they receive high radiation dose and carry a high weighting factor in ICRP 103.\textsuperscript{41} In chest anteroposterior and left lateral examinations, the breasts were directly irradiated without any other body shielding, so the dose received does not depend on the body dimension. Thus, $R^2$ value for breasts (Table 10) for the anteroposterior study was very small (0.008).

Correlations between the body diameter and the normalized lung and liver doses were better than that of the breasts for all modalities, indicating surface organs have weaker correlation with body size, which agreed well with previous studies.\textsuperscript{16, 61} The exponential relationship between organ dose normalized to mAs and body size shown in this study has also been reported in the literature;\textsuperscript{61, 75, 76} our study further demonstrated such an exponential relationship for chest tomosynthesis examinations.

The absolute effective dose from the chest CT examination increased exponentially with the increase of patient size, but it only increased slightly for radiographic modalities. This is caused by the accumulation of dose from the many projections acquired in CT. With the effective dose per mAs or 100 mAs known for different body sizes and for both planer x-ray and CT, the absolute effective dose can be expressed as $(ED/mAs) \times mAs$, where mAs is proportional to the incident exposure. From
Figure 9a, 3d and Table 9, the ED/mAs or ED/100 mAs decreased at a similar rate with respect to patient size for the chest posteroanterior and CT examinations. Thus, the different trends of absolute effective dose between these two examinations can be explained by the difference of incident exposure, explored in the following. To understand this hypothesis, assume two patients with average body size $d_1$ and $d_2$ and incident exposure of $X_1$ and $X_2$ in a posteroanterior exam. In order to have the same noise level, the exposure at the detector ($X_1e^{-\mu d_1}$ for patient #1 and $X_2e^{-\mu d_2}$ for patient #2) should be the same, which is the rationale behind the automatic exposure control. This results in the ratio of $X_1$ to $X_2$ to be $e^{\mu(d_1-d_2)}$. For CT, many such projections are acquired. To simplify the scenario, assume 360 projections and the patients having cylindrical body shape. The ratio of the total exposure $X_1$ to $X_2$ becomes $e^{\mu(d_1-d_2)\times360}$, which means for different sized patients, the incident exposure differences need to be much larger for CT than for the posteroanterior examination to remain at the same noise level. As stated in the beginning of this paragraph, ED/mAs or 100 mAs varies at similar rates for CT and posteroanterior examinations, the tremendous difference in incident exposure largely determines the differences in absolute effective dose trends between these two examinations. The results for absolute effective doses indicate that a larger patient would benefit much more by choosing chest tomosynthesis as opposed to chest CT. However, to have a thorough picture, the image quality should be assessed for different size patients as well, a subject for future investigation.
Recognizing the limitations of effective dose, cancer risk was estimated using the risk index concept for each modality. The trends of risk index for the various modalities were similar to that of effective dose, which follows the same argument with the additional provision of accounting for patient gender.

### 3.4.3 Effect of tomosynthesis angles on radiation dose

Effective doses and doses to lungs and breasts for each projection angle in chest tomosynthesis displayed a parabolic shape, as reported in other studies. Since the same collimation was used throughout all projection angles, the parabolic response was mainly due to the change of field-to-source distance from extreme to central angles and thus the inverse square effect on incident exposure. Dose to the liver, however, did not have the maximum at zero degrees, which was because of more shielding for body tissues at lower angles caused by its inferior location with respect to the pivot point.

### 3.4.4 Limitations and future work

It should be noted that the primary purpose of this study was to provide dosimetric information between chest x-ray radiography, tomosynthesis, and CT. The data reported here are entitled to determine the best imaging modality for individual patients. However, to have a thorough picture, the image quality of the three modalities and thus the benefit to risk ratios should also be considered. For example, although larger patients receive much less dose during a chest tomosynthesis examination than CT compared to smaller patients, the image quality from a tomosynthesis scan might be
much worse for larger patients which might result in a smaller benefit to risk ratio. Furthermore, future work should consider patients’ age while computing risk index, since age dependency is one significant advantage of the concept of risk index over effective dose as a dose metric. This study can also be extended to pediatric patients, who are more radio-sensitive and have a longer life time to develop cancers. However, one major conclusion from this study that can also be applied to pediatric patients is that the effective dose ratio between CT and tomosynthesis might be less for pediatric patients.

3.5 Conclusion

In this study, organ doses, effective doses, and risk indices were compared across three main x-ray based chest imaging modalities based on one common Monte Carlo simulation platform. Fifty-nine anatomical variable male and female adult patients covering a wide range of body habitus were employed in the Monte Carlo simulation of each modality. The average effective dose of the chest posteroanterior examination was found to be 0.04 mSv, which was 1.3% that of the chest CT examination. The average effective dose of the chest tomosynthesis examination was found to be about ten times that of the chest posteroanterior examination and about 12% that of the chest CT examination. While these results are affected by the exact protocols modeled for each modality, this paper provides the dose data normalized by mAs or CTDI\textsubscript{vol} to enable modality dose calculation for alternative protocols. With increasing patient average
chest diameter, both the effective dose and risk index for CT increased considerably in an exponential fashion, while these two dose metrics only increased slightly for radiographic modalities and tomosynthesis. The effective dose ratio and risk index ratio versus chest diameter of the chest CT with tomosynthesis showed a significant slope, while the ratios of chest tomosynthesis with the conventional two-view chest x-ray remained rather flat, indicating a greater benefit to radiation risk ratio for larger patients when choosing chest tomosynthesis rather than chest CT. Effective and organ doses normalized to mAs all illustrated an exponential decrease with increasing patient size. Surface organ breasts had less correlation with body size than lungs and liver. Effective and organ doses at each projection angle in chest tomosynthesis showed a parabolic shape.
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