A database of 40 patient-based computational models for benchmarking organ dose estimates in CT

Running title: Database for benchmarking CT organ dose

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Purpose. Patient radiation burden in CT can best be characterized through risk estimates derived from organ doses. Organ doses can be estimated by Monte Carlo simulations of the CT procedures on computational phantoms assumed to emulate the patients. However, the results are subject to uncertainties related to how accurately the patient and CT procedure are modeled. Different methods can lead to different results. This paper, based on decades of organ dosimetry research, offers a database of CT scans, scan specifics, and organ doses computed using a validated Monte Carlo simulation of each patient and acquisition. It is aimed that the database can serve as means to benchmark different organ dose estimation methods against a benchmark dataset.

Acquisition and Validation Methods. Organ doses were estimated for 40 adult patients (22 female, 18 female) who underwent Chest and Abdominopelvic CT examinations. Patient-based computational models were created for each patient including 26 organs for female and 25 organs for male cases. A Monte Carlo code, previously validated experimentally, was applied to calculate organ doses under constant and two modulated tube current conditions.

Data Format and Usage Notes. The generated database reports organ dose values for Chest and Abdominopelvic examinations per patient and imaging condition. Patient information and images and scan specifications (energy spectrum, bowtie filter specification, and tube current profiles) are provided. The database is available at publicly accessible digital repositories.

Potential Applications. Consistency in patient risk estimation, and associated justification and optimization requires accuracy and consistency in organ dose estimation. The database provided in this paper is a helpful tool to benchmark different organ dose estimation methodologies to facilitate comparisons, assess uncertainties, and improve assessment of risk of CT scans based on organ dose.

Key words: CT organ dose, benchmark, database, uncertainties, Monte Carlo
1. INTRODUCTION

Characterizing patient-specific radiation dose in CT has emerged as an important component of CT imaging practice. Amongst various dose metrics, absorbed organ dose is generally regarded as the best metric to quantify radiation dose, from which the total individual radiation burden can be estimated. Over the past decade, significant progress has been made to quantify organ dose through various estimation and validation techniques [1-8]. Despite the continuing efforts, there arises a necessity to understand the uncertainties associated with these estimation methods. The quantification of uncertainty in the process can provide an understanding of the limitations and potential improvement of current dose estimation methods.

Organ dose represents the magnitude and distribution pattern of energy deposition of ionization radiation in the human body. Since it is impractical to directly measure the dose distributed inside a living body, the best technique is to estimate organ dose by Monte Carlo (MC) simulation of the CT acquisition process on representational phantoms. The estimation accuracy is critically dependent on how well the method models the patient and exposure condition, including the patient anatomical characteristics and the x-ray irradiation condition of the scanner. In addition, the administration of iodinated contrast medium may have an influence. Uncertainties are further induced due to variation in the approaches used to model the above factors.

Currently, there are a number of implementations to estimate organ dose. The purpose of this paper is to offer a database so that developers can benchmark their organ dose estimation and associated uncertainties against a benchmark dataset. The database includes 40 individual CT scans under precise irradiation conditions. Validated organ dose values are further provided, estimated considering the exact scanner and anatomical details of each patient. It is envisioned that others use their methodology to estimate the organ dose for the patients in this database using the defined irradiation conditions and compare the results in the values offered in the database.

2. ACQUISITION AND VALIDATION METHODS

Clinical CT images for 40 adult patients (22 male, 18 female; age range: 18-78 years) were used to estimate organ doses. Using previously validated methods, whole-body computational models were created for each patient [9, 10]. In particular, for each patient dataset, the bones and major organs were manually segmented.
using a software application developed in our laboratory (ImageSegment, RAILabs, Duke University). 3D polygon surfaces were fit to each segmented structure using the marching cubes algorithm of the Visualization Toolkit (www.vtk.org) and the surfaces were compiled into an initial patient model. Structures that could not be segmented from the CT data were filled in using template anatomies. A pre-existing computational phantom from the XCAT library [9, 10], containing all organs and structures, was selected to best match the patient’s characteristics (sex, age, height, weight). Voxelized images were generated from the template XCAT and initial patient model setting the organs and structures to corresponding intensities. From these images, the multichannel large deformation diffeomorphic metric mapping (MC-LDDMM) method [11] was used to calculate the transform from the template XCAT to the patient target. The transform was then applied to the XCAT template to fill in the remaining anatomy, creating a complete computational model for each case.

The computational models were voxelized (3.45 mm resolution) and input into a Monte Carlo simulation program. Following ICRP 89 and ICRP 103 recommendations [12, 13], the computational models include 26 organs for female patients and 25 organs for male patients as reported in the organ dose folder files.

The organ dose values were estimated and provided for each patient undergoing chest and abdominopelvic CT examinations using an established and previously validated Monte Carlo method. The program, detailed elsewhere [6, 14, 15], is based on PENELlope (Universitat de Barcelona, Spain). The patient models is defined within the Monte Carlo geometry. The impinging photons, following the energy distribution of the spectrum, are attenuated through the bow-tie filter and the body habitus. The flux of photons are defined according to the tube current profile (either fixed or modulated). Organ dose was estimated by tallying the energy deposited in each organ. CTDI is likewise estimated by defining a CTDI phantom in the Monte Carlo program. Thus organ doses can be normalized to the CTDI applied for a particular examination.

Organ doses were estimated under three examination conditions: (1) fixed tube current, (2) tube current modulation (TCM) exams with modest modulation strength (alpha = 0.5), and (3) TCM exams with strong modulation strength (alpha = 1). The study considered one scanner model from one vendor with a tube voltage of 120 kVp and a bowtie filter attenuation as a function of energy listed in the CT_Acquisition_Condition folder. Scanner parameters (including pitch, collimation, effective beam width, and scanning length), image details, and patient age and gender are listed in the file Patient_information.xlsx.
Doses were estimated based on an exam CTDI$_{vol}$ of 7.03 mGy. For a CTDI$_{vol}$ value other than that used, the reported organ dose values can be linearly adjusted up or down.

3. DATA FORMAT

The database is publicly available via the CERN’s Zenodo repository (https://doi.org/10.5281/zenodo.3579490), and The Cancer Imaging Archive (TCIA – https://www.cancerimagingarchive.net/). Any publication of results obtained with this dataset should reference this paper.

The dataset includes clinical image cases for 40 adult patients (22 male, 18 female) for chest and abdominopelvic CT examinations with corresponding slices provided. The folder CT_Acquisition_Conditions includes scan specifications (energy spectrum, bowtie filter specification, and tube current profiles) for each patient and each modulation type. Patient information and images are included in the folder Patient-Images. The organ dose values for chest and abdominopelvic examinations for each of the three irradiation conditions simulated are in the folder Organ_Dose. The materials that are provided as a part of this benchmark database are listed in Table 1.

4. DISCUSSION

In this paper, we provide a database of patient images and associated verified MC based estimates of organ doses that may be used for benchmarking different organ dose estimation techniques against a benchmark standard. There are multiple sources of uncertainties associated with organ dose estimation in CT. Those are related to the exact correspondence of the patient geometry to the representational model used, the accuracy of the modeling of x-ray irradiation condition, and the simplification of irradiation condition associated with TCM. The database offered here can be used to ascertain the quantities of these uncertainties. There is also uncertainty associated with the presence of iodine contrast medium, which is not a focus of this database. Table 2 offers a summary of factors and their general magnitude of associated uncertainty. Below we offer a discussion of some of these factor along the three main category of patient and scan representation.

4.1. Patient representation
The uncertainty associated with computational phantoms refers to how accurately a representing model resembles the anatomical structure of the actual patient. Currently, three types of computational phantoms are available for organ dose estimation, namely, stylized phantoms, voxelized phantoms, and hybrid phantoms.

The uncertainties associated with using different types of computational phantoms have been previously reported in several studies. Zhang et al assessed the organ dose uncertainties associated with four types of phantoms (ICRP, CT-Expo, XCAT, and IMPACT) for ten body and three neurological CT protocols [16]. With one single dose estimation technique used across all phantoms, the average percentage differences were in the range of 3%-38% for fully irradiated organs and 7%-66% for partially irradiated organs, respectively. Sizable differences were found for organs that located near the scan boundary (e.g., testes for abdominopelvic examination and colon for chest examination). Furthermore, noticeable uncertainties were found for organs with different spatial distribution across phantoms (e.g. breasts for female phantoms). Liu et al compared the organ dose differences between RPI and ICRP reference phantoms for chest, abdominopelvic, and chest-abdomen-pelvis protocols [17]. It was found that the ratio between the organ doses for the two types of phantoms were within the range of 0.75-1.16 for the majority of fully irradiated organs. However, significant differences were found for organs near the scan start/end location. In both studies, uncertainties were mainly introduced by variation in organ location and spatial distribution.

The above-mentioned studies highlight the need for phantoms that can realistically mimic human features. However, even in the presence of a library of diverse human models, to achieve accurate dose estimation, a clinical patient needs to be optimally matched to a model in the library. The quality of the matching can significantly impact the organ dose estimation accuracy. Tian et al assessed the uncertainties associated with patient matching to tens of computational phantoms for chest and abdominopelvic exams [14]. The matching process was based on patient size estimated from the patient localizer image. The organ dose differences between the matched patient pairs were on average 11% and 15% for chest and abdominopelvic examinations, respectively. The largest uncertainties were again found for small organs near the scan start/end region (e.g., testes for abdominopelvic examination and thyroid for chest examination).

### 4.2. Scan representation

The uncertainty associated with the scanner irradiation condition refers to how the technique models the scanner radiation, including geometry and physical properties of the CT scanner, scanning collimation, start
and end tube angle positions, over-ranging distance, and the tube current modulation (TCM) technique. Furthermore, some levels of uncertainties are associated with Monte Carlo simulation packages used for the estimation.

Mostly associated with helical CT, the uncertainties associated with tube start/end location are mainly induced by the helical trajectory of the CT source, which creates a periodical dose pattern across patient body. Such heterogeneous distribution of the scanner output radiation results in “hot spots” and “cold spots” in different organs. Zhang et al studied the effect of tube start/end location under different conditions (e.g., pitch, collimation) for different patient models (infant, small child, adult female, and pregnant patient) [18]. It was found that the largest dose variations occur for eye lens, thyroid, breasts, and testes, all of which are at or near the surface of the patient. The uncertainties were in the range of 10%-33% across different phantoms for the small surface organs. Similar results were found by Li et al [19]. The uncertainties were generally higher for small peripheral organs (e.g., breast, testes) and for organs on the edge of scan coverage (e.g., gall bladder in chest scan, and breast in the abdominopelvic scan). However, the uncertainties were generally found to be within 10% for the majority of organs.

Another main source of organ dose uncertainties is the modeling of tube current modulation in examinations conducted with automatic exposure control. Modeling TCM requires effective quantification of dose field distribution created by the changing tube current. As the tube current is changing dynamically across patient body habitus, the scanner reported CTDI_{vol} estimated using the average tube current does not reflect the local dose field of a given organ. As illustrated by Schlattl et al, there can be significant differences (>50%) when using scanner reported CTDI_{vol} with fixed tube current organ dose coefficients to approximate organ dose [4]. Khatonabadi et al and Li et al have demonstrated the use of a regional CTDI_{vol} estimated by averaging the tube current values within the organ region to approximate organ dose under TCM [15, 20]. The uncertainties associated with such techniques were found to be generally with 20% for most of the organs, with the expectation of organs located in the pelvic and shoulder regions. With the inclusion of the scattered dose distribution by convolving the TCM profile with the dose rate profile of the scanner [10], the uncertainties associated with TCM approximation can be reduced to within 10% across different organs.

In addition to the uncertainty associated with geometry and irradiation condition of the scan, there is also uncertainty associated with the statistical fluctuations associated with any Monte Carlo simulation as well as that associated with the underlying differences in the physical models used by different implementations. The
latter uncertainties are generally small and within 5-10%. As the organ dose is an average over a large volume of tissue, they generally exceed those associated with the statistical uncertainties, which is normally in 1-2% range [21].

4.3. Other factors

While not an explicit focus of the present work, the iodinated contrast medium can influence radiation dose. At kilovoltage energies, the high photoelectric cross section of iodine result in substantial photoelectric interaction. The high linear energy transfer and short range of the photoelectric interaction products (photoelectrons, characteristic x-rays and Auger electrons) and free radicals produce a localized dose enhancement. Recently, several studies have assessed the dose increase due to the presence of contrast media. In Sahbaee et al, organ dose was estimated for uni-phasic and bi-phasic injection protocols. The injection of contrast medium resulted in up to 52% increase of kidney dose and 22% of liver dose [22, 23]. In Tran et al, the organ dose increased 361% in kidney, 379% in adrenals, and 266% in spleen compared with non-contrast exam for a standard clinical contrast-enhanced body CT examination [24]. The two studies make differing assumption about the proximity of the medium to the cellular structure, and thus the difference in the estimated dose values. To what extend those enhanced dose values corresponded to increased radiation burden to biological tissue (as opposed to the contrast medium alone) is a topic that requires further investigation. However, the presence of contrast medium and its proximity to biological tissue can have a non-negligible effect on organ dose.

5. CONCLUSION

Absorbed organ dose is essential for the calculation of several radiation metrics and surrogates (i.e., effective dose and risk index [13, 25]). Such metrics are critical for justification and optimization of the procedures and for the comparison with local, national, and international reference levels. Because there are many methodologies to estimate organ dose and there are multiple sources of uncertainties associated with it, each methodology can be benchmarked with the database presented in this paper to achieve consistency in risk estimation and comparison across institutions.

6. REFERENCES


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**7. CONFLICT OF INTEREST STATEMENT**

Ehsan Samei lists relationships with the following entities unrelated to the present publication: GE, Siemens, Bracco, Imalogix, 12Sigma, SunNuclear, Metis Health Analytics, Cambridge University Press, and Wiley and Sons.
Table 1. Description of the files provided for the benchmark dose database.

<table>
<thead>
<tr>
<th>Folder/subfolder</th>
<th>File name</th>
<th>File description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patient_Images</td>
<td>Patient_information.xlsx</td>
<td>Patient number, age, gender, scan condition, and image details</td>
</tr>
<tr>
<td>Chest and Abdo sub-folders</td>
<td>pt#_x_y_z_16bits.raw (# is the patient number, x, y, and z are the number of voxels in the x, y, z directions)</td>
<td>40 clinical CT image cases Format: 16 bits signed, big-endian byte order</td>
</tr>
<tr>
<td>CT_Acquisition_Condition</td>
<td>Acquisition_Spectrum_PreBowtie_120kvp.xlsx</td>
<td>X-ray spectrum file prior to bowtie filter</td>
</tr>
<tr>
<td></td>
<td>Bowtie_energy.xlsx</td>
<td>Attenuation of the bowtie filter as a function of energy (in 1st row in eV) and angle (in 1st column in radian).</td>
</tr>
<tr>
<td>TCM_Profile sub-folder</td>
<td>pt#_XYZ_TCM_Profile.txt (# is the patient number)</td>
<td>Tube current value as a function of tube rotation angle and Z. The first column is Z, second, the angle of the tube (beta, in radian), third, the mA.</td>
</tr>
<tr>
<td>Alpha_0.5 and Alpha_1 sub-sub-folders</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Organ_Dose</td>
<td>Chest_Alpha_0.5.xlsx</td>
<td>Absorbed organ dose values for chest and abdominopelvic examinations for each of the three irradiation conditions simulated (Fixed Tube Current, TCM alpha=0.5, TCM alpha=1)</td>
</tr>
</tbody>
</table>
Table 2. Summary of the sources and level of uncertainties in organ dose estimation

<table>
<thead>
<tr>
<th>Source</th>
<th>Description</th>
<th>Magnitude of associate uncertainty [related references]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computational phantoms</td>
<td>Accuracy of how well different types of computational phantoms resemble the anatomical structure of the actual patient</td>
<td>3%-66% [16, 17]</td>
</tr>
<tr>
<td>Patient matching</td>
<td>Mismatching induced by geometry difference between a clinical patient to a matched computational phantom</td>
<td>10%-15% [14]</td>
</tr>
<tr>
<td>Scan location</td>
<td>Organ start/end location induced by the heterogeneous dose pattern created across the patient’s body by the helical trajectory of the CT source.</td>
<td>&lt;10% for most organs 10%-33% for the small surface organs [18, 19]</td>
</tr>
<tr>
<td>TCM representation</td>
<td>Induced by using simplified tube current profiles (z-dimensional) to approximate organ dose under TCM</td>
<td>0%-20% depending on the method used to model the dose field under TCM [10, 15, 20]</td>
</tr>
<tr>
<td>Monte Carlo simulation</td>
<td>Mainly caused by the underlying differences in the physical models used by different codes.</td>
<td>5-10% [21]</td>
</tr>
<tr>
<td>Contrast medium</td>
<td>Induced by the photoelectric interaction products of the contrast medium</td>
<td>Reported 22-379% depending on organ, injection protocols, and assumptions made [22, 23, 24]</td>
</tr>
</tbody>
</table>