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A feasibility study to reduce misclassification error in occupational dose estimates for epidemiological studies using body size-dependent computational phantoms

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Abstract

In the epidemiological study on the health effects of participants in the United States Radiologic Technologists (USRT) study, organ dosimetry was performed based on surveys and literature reviews. To convert dosimeter readings to organ doses, organ dose coefficients were adopted. However, the existing dose coefficients were derived from computational human phantoms with ICRP reference height and weight not accounting for the variation in body size. We first calculated preliminary body size-dependent organ dose coefficients using selected body size-dependent phantoms combined with Monte Carlo radiation transport method. We then tested the accuracy of these body-size dependent coefficients against the ICRP 74 reference size coefficients in comparison with five individual-specific organ dose coefficients computed from computed tomography (CT) image-based anatomical models of five adult males with different body sizes also using Monte Carlo methods. The reference size dose coefficients overall underestimate the patient-specific dose coefficients by up to 51%. Body size-dependent phantoms overall provided more accurate organ dose coefficients for the five patients. In case of the esophagus, the dose underestimation of 51% in the comparison with the reference phantom was reduced to 7%. The results confirm that potential dosimetric misclassification caused by using reference size phantom-based dose coefficients can be resolved by using the body size-dependent dose coefficients.

Keywords

epidemiology; dose reconstruction; body size; computational human phantoms; organ dose coefficients

I. Introduction

Epidemiological studies of cancer risk in populations exposed to radiation require individualized organ doses for each cohort member for accurate risk estimation [1]. However, it is often challenging to reconstruct individualized organ doses because radiation exposure events took place years ago and therefore limited data on radiation exposure for epidemiological cohorts are available at the time of dosimetry. Hence, most dose reconstruction studies for retrospective epidemiological studies rely on surveys, historical literature reviews, and reference dosimetry data.

In the epidemiological study at the National Cancer Institute on the health effects of United States Radiologic Technologists (USRT), organ dose reconstruction was performed based on dosimeter badge dose records and organ dose coefficients, converting dosimeter reading to organ absorbed dose [2]. The dose coefficients from the International Commission on Radiological Protection (ICRP) Publication 74 [3] were adopted, which were derived from reference size stylized computational human phantoms [4] combined with Monte Carlo radiation transport techniques. Although the ICRP 74 dose coefficients may reasonably estimate organ dose for cohort members with body size close to the reference size, it must be noted that body size may significantly affect internal organ dose in external radiation exposure scenarios because of the shielding effect from overlying adipose tissue surrounding the torso [5]–[8]. Without body size incorporated into dosimetry, organ dose to cohort members can be over- or under-estimated, which will consequently cause misclassification of organ dose in risk analysis.

After the introduction of the reference size stylized computational phantoms [4], the format of phantoms has evolved through more realistic voxel format based on tomographic radiological images into flexible surface format [9]. Thanks to the flexibility of the surface-format (also called hybrid or boundary-representation) phantoms, the body shape of a reference size phantom can be modified to represent under- or overweight individuals. Several research groups have introduced a library of body size-dependent computational phantoms [9]–[12] including the phantom library developed in collaboration between the University of Florida and National Cancer Institute [11]. Computational human phantoms representing different body size have been used in CT dosimetry to better individualize organ dose estimates [6]–[8], [13]. However, the phantoms with different body sizes have not been used for body size-specific dose assessment in occupational exposure scenarios.

In the current study, we explored the feasibility to reduce potential misclassification error in retrospective dose reconstruction studies by using the body size-dependent phantom library. We used the occupational exposure scenario of the USRT study as an example. We first calculated preliminary body size-dependent organ dose coefficients using selected body size-dependent phantoms. We then tested the accuracy of these body-size dependent coefficients against the ICRP 74 reference size coefficients in comparison with five individual-specific organ dose coefficients computed from computed tomography (CT) images-based anatomical models of five adult males with different body sizes combined with Monte Carlo radiation transport methods.

II. Methods

A. Body size-dependent phantoms

To generate body size-dependent organ dose coefficients, we adopted the library of body size-dependent computational human phantoms [11]. The phantom library includes a total of 351 pediatric and adult phantoms with over a range of heights and weight. We selected the five adult male phantoms with the height of 175 cm and the weight of 60, 70, 80, 100, and 130 kg. We fixed height assuming that height would not have as much impact on organ dose for whole body external photon irradiation compared to weight variation. The original mesh format phantoms were voxelized into the voxel resolution of $0.1579 \times 0.1579 \times 0.2207 \text{ cm}^3$, which provides the smallest voxels equivalent to the reference thickness of skin defined in the ICRP Publication 89 [14].

B. Patient CT data

To test the performance of dose coefficients from reference size phantom and the body size-dependent phantoms, we calculated organ dose coefficients from five adult male patients (considered ground truth), selected from the CT archive at the National Institutes of Health Clinical Center. The patients' average age was 58 years (28 to 72 years) with the average height of 176 cm (172 to 179 cm) and the weight of 60, 70, 80, 100, and 130 kg. We contoured the esophagus, heart, lungs, skeleton, and body contours by using the Eclipse™ (Varian Medical System Inc., Palo Alto, CA) Treatment Planning System (TPS). The brush and interpolate function built in the Eclipse was used to help semi-automatic contouring of the organs and tissues. The organ and tissue models in polygon mesh format extracted from Eclipse were then processed in a 3D modeling program, Rhino 5.0™ (McNeel North America, Seattle, WA) and ImageJ [15] to prepare the input files for Monte Carlo radiation transport. The voxel resolution of $0.2 \times 0.2 \times 0.4 \text{ cm}^3$ was used for all phantoms. Table 1 shows the mass of the lungs, esophagus, and heart of the five patients and five body size-dependent phantoms.

Prior to dose comparison, we also intended to test the hypothesis that there is significant correlation between the depth of organs from the body surface and the weight of patients, which is directly related to the next hypothesis that body size-dependent phantom can increase the accuracy in organ dose prediction for patients with different body size. To test the first hypothesis, the depth of esophagus from the frontal body surface at different level of vertebrae from the 7th cervical vertebrae (C7) down to Gastro-Esophageal Junction (GE) was manually measured for the five patients in Eclipse.

C. Monte Carlo organ dose calculations

A general-purpose Monte Carlo radiation transport code, MCNPX 2.7 [16], was employed for calculating organ dose coefficients. We calculated radiation dose to the lungs, heart, and esophagus, three key organs of interest in the USRT study, in the antero-posterior (AP) irradiation geometry, which is most common in occupational exposure [2] and was assumed as the exposure geometry in the USRT cohort. Dose calculations were conducted for the five sets of body size-dependent phantoms and five patient models. Broad and parallel photon beam with the size of $100 \times 200 \text{ cm}^2$ covering the whole body of the phantoms and patient

models was simulated, which was also assumed in the previous dose assessment in the USRT cohort. Different from ICRP Publication 74 [3] where the kerma approximation was assumed, we followed secondary electrons in our dose calculations. Photon dose coefficients, which are the ratio of organ absorbed dose (Gy) to air kerma (Gy), were calculated for the lungs, heart, and esophagus for 24 mono photon energies (0.01 – 10 MeV). We confirmed that the relative error from Monte Carlo calculations was less than 1% for all three organs for the energy of photons greater than 0.1 MeV. The calculations were conducted using the computational resources of the NIH HPC Biowulf cluster (<https://hpc.nih.gov>).

III. Results

Figure 1 shows the depth of the esophagus from the frontal body surface for the five patients with the weight of 60, 70, 80, 100, and 130 kg at different vertebral landmarks. We found a strong correlation between body weight and esophageal depth ($R^2=0.869$ at the level of T7). The depth for the 130 kg patient (15.0 cm) was about two-fold greater than that of 60 kg patient (7.3 cm).

Dose coefficients (Gy/Gy) for the five patients and five body size-dependent phantoms are tabulated in Table A1 to A3 for the lungs, heart, and esophagus, respectively. Figure 2 shows the comparison of dose coefficients for (a) lungs, (b) heart, and (c) esophagus between the patient models (solid lines) and the body size-dependent phantoms (dotted lines).

Table II shows the comparison of the patient-specific doses (ground truth) calculated from the five patient models with the data from the reference size phantom (old method, ICRP 74) and body size-dependent phantoms (newly proposed method). The reference phantom-based dose coefficients overall underestimate the patient-specific organ dose by up to 51% (esophagus of the 130 kg patient). Greater underestimations of dose were found for patients with greater body weight: 7% for the 60 kg patient vs. 51% for the 130 kg patient.

IV. Discussion

We conducted the current study to test if our body size-dependent phantom library can be used to increase the dosimetric accuracy for the USRT study cohort members whose body size is available by comparing the body size-dependent dose coefficients with the old values based on the stylized phantoms with reference body size.

First, we investigated the correlation between the depth of the esophagus from the body surface and the esophageal dose in AP irradiation geometry. We confirmed that the results support the hypothesis that there is significant correlation between the depth of organs from the body surface and the weight of patients. Then, we calculated dose coefficients for the five patients and five size-matched phantoms. As expected from the relationship between the esophagus depth and body weight, the patients and phantoms with greater body weight showed low dose coefficients since photons would experience more attenuation while penetrating the thicker adipose layers in overweight bodies compared to underweight ones.

Finally, from the comparison of dose difference between patient-to-ICRP 74 and patient-to-body size-dependent phantoms showed that body size-dependent phantoms overall provided more accurate organ dose coefficients for the five patients. In case of the esophagus, the dose difference of -51% for the comparison with the reference phantom to the ground truth dose was reduced to 7%. Dose agreement improved for the patients with greater weight whereas smaller weighted patients did not show much improvement. It must be noted that as shown in Figure 2, the variation of dose coefficients by body weight decreases as the photon energy increases, which means the improvement in dosimetric accuracy by using body size-dependent phantoms would also relatively decrease at higher energies. Figure 3 more clearly demonstrates the advantage of using body size-dependent dose coefficients against the reference phantom-based dose coefficients. The results confirm that potential dosimetric error and corresponding dose misclassification caused by the dose coefficients from the reference size phantom can be resolved by using the dose coefficients derived from body size-dependent computational human phantoms.

The authors are aware of some limitations of the current study. First, the sample size of patients is too small to clearly demonstrate the advantage of the body size-dependent dose coefficients. Second, although about 73% of the USRT cohort members is female, only male patients and phantoms were used in this study. After confirming the feasibility of the new concept from the results of the current study, however, we are now expanding the dose comparison to include over 60 adult male and female patients.

V. Conclusion

We evaluated the feasibility of resolving the potential misclassification of organ dose caused by not accounting for body size in organ dose estimations. We confirmed that new organ dose coefficients derived from body size-dependent phantoms can more accurately estimate organ doses for patients with different body size. Following the preliminary dose coefficients calculated in this study, we plan to establish more comprehensive sets of organ dose coefficients using the library of body size-dependent adult male and female phantoms. We then plan to update the previous organ dose data for the USRT study by using the new set of body size-dependent organ dose coefficients. Furthermore, the new dose coefficients can be utilized in other epidemiological studies of health effect in occupational radiation exposures where the information about body size is available for cohort members.

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Appendix

TABLE A1

Absorbed dose per unit air kerma (Gy/Gy) for the **lungs** in the patients with five different body weights and the phantoms with the weight matching those of the patients.

Lungs Energy (MeV)	Patients					Phantoms				
	60	70	80	100	130	60	70	80	100	130
0.01	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.015	0.0118	0.0014	0.0002	0.0033	0.0003	0.0016	0.0008	0.0008	0.0001	0.0000
0.02	0.0782	0.0287	0.0080	0.0454	0.0104	0.0353	0.0235	0.0213	0.0095	0.0010
0.03	0.4525	0.3217	0.1629	0.3800	0.1612	0.3093	0.2589	0.2406	0.1703	0.0599
0.04	0.8221	0.6972	0.4338	0.7510	0.4182	0.6850	0.6120	0.5813	0.4661	0.2365
0.05	1.0786	0.9886	0.6801	1.0234	0.6528	1.0021	0.9219	0.8909	0.7539	0.4459
0.06	1.2173	1.1591	0.8473	1.1718	0.8066	1.1909	1.1190	1.0896	0.9494	0.6157
0.07	1.2322	1.2013	0.9030	1.1933	0.8648	1.2728	1.2085	1.1822	1.0461	0.7129
0.08	1.2490	1.2235	0.9431	1.2130	0.9091	1.2999	1.2444	1.2214	1.0951	0.7618
0.1	1.1909	1.1815	0.9250	1.1610	0.8968	1.2744	1.2244	1.2064	1.0901	0.7830
0.2	1.0392	1.0145	0.8227	1.0065	0.8043	1.1064	1.0669	1.0576	0.9649	0.7186
0.3	1.0069	0.9756	0.8071	0.9773	0.7942	1.0551	1.0218	1.0123	0.9318	0.7080
0.4	0.9886	0.9565	0.8038	0.9621	0.7943	1.0303	1.0016	0.9918	0.9182	0.7129
0.5	0.9827	0.9497	0.8096	0.9573	0.7998	1.0165	0.9898	0.9814	0.9138	0.7209
0.6	0.9793	0.9472	0.8161	0.9569	0.8081	1.0108	0.9848	0.9760	0.9124	0.7301
0.8	0.9809	0.9487	0.8293	0.9621	0.8247	1.0055	0.9840	0.9757	0.9185	0.7501
1	0.9903	0.9589	0.8500	0.9726	0.8444	1.0015	0.9816	0.9741	0.9221	0.7664
2	0.9937	0.9656	0.8846	0.9808	0.8807	1.0077	0.9913	0.9864	0.9488	0.8261
3	0.9993	0.9746	0.9067	0.9901	0.9031	1.0195	1.0048	0.9980	0.9655	0.8642
4	1.0038	0.9812	0.9194	0.9965	0.9161	1.0294	1.0152	1.0092	0.9799	0.8893
5	1.0004	0.9782	0.9210	0.9932	0.9187	1.0374	1.0235	1.0186	0.9924	0.9079
6	0.9974	0.9766	0.9224	0.9909	0.9199	1.0397	1.0256	1.0195	0.9952	0.9155
8	0.9942	0.9751	0.9247	0.9884	0.9217	1.0330	1.0214	1.0153	0.9951	0.9253
10	0.9918	0.9734	0.9260	0.9867	0.9224	1.0226	1.0190	1.0135	0.9948	0.9322

TABLE A2

Absorbed dose per unit air kerma (Gy/Gy) for the **heart** in the patients with five different body weights and the phantoms with the weight matching those of the patients.

Heart Energy (MeV)	Patients					Phantoms				
	60	70	80	100	130	60	70	80	100	130
0.01	0.0120	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.015	0.0531	0.0002	0.0001	0.0002	0.0000	0.0017	0.0008	0.0007	0.0001	0.0000
0.02	0.1456	0.0108	0.0076	0.0101	0.0025	0.0327	0.0221	0.0191	0.0072	0.0005
0.03	0.6163	0.2274	0.1771	0.2061	0.1066	0.3055	0.2600	0.2248	0.1508	0.0490
0.04	1.0958	0.6283	0.5262	0.5559	0.3859	0.7431	0.6688	0.6083	0.4744	0.2333

Heart	Energy (MeV)	Patients					Phantoms				
		60	70	80	100	130	60	70	80	100	130
	0.05	1.4217	1.0045	0.8730	0.8634	0.6802	1.1248	1.0463	0.9827	0.8178	0.4737
	0.06	1.5949	1.2438	1.1233	1.0626	0.9098	1.3565	1.2849	1.2313	1.0575	0.6808
	0.07	1.5919	1.3238	1.2154	1.1206	0.9935	1.4598	1.4039	1.3521	1.1888	0.8011
	0.08	1.6042	1.3666	1.2452	1.1414	1.0545	1.4792	1.4341	1.3929	1.2380	0.8675
	0.1	1.5096	1.3192	1.2215	1.1101	1.0459	1.4337	1.3922	1.3594	1.2254	0.8883
	0.2	1.2392	1.0856	1.0123	0.9285	0.8856	1.1722	1.1462	1.1271	1.0250	0.7728
	0.3	1.1551	1.0106	0.9533	0.8955	0.8439	1.0876	1.0620	1.0510	0.9627	0.7394
	0.4	1.1059	0.9727	0.9215	0.8798	0.8277	1.0461	1.0253	1.0137	0.9347	0.7291
	0.5	1.0819	0.9582	0.9119	0.8756	0.8267	1.0217	1.0025	0.9891	0.9147	0.7304
	0.6	1.0663	0.9504	0.9055	0.8718	0.8263	1.0076	0.9930	0.9796	0.9109	0.7333
	0.8	1.0527	0.9457	0.9069	0.8813	0.8310	0.9926	0.9786	0.9665	0.9049	0.7465
	1	1.0500	0.9520	0.9174	0.8943	0.8469	0.9892	0.9750	0.9621	0.9072	0.7560
	2	1.0242	0.9498	0.9228	0.9164	0.8735	0.9936	0.9804	0.9647	0.9205	0.8043
	3	1.0230	0.9566	0.9350	0.9334	0.8929	0.9995	0.9840	0.9750	0.9401	0.8395
	4	1.0223	0.9647	0.9426	0.9424	0.9074	1.0066	0.9910	0.9817	0.9485	0.8618
	5	1.0155	0.9608	0.9394	0.9441	0.9078	1.0074	0.9921	0.9852	0.9575	0.8713
	6	1.0104	0.9587	0.9377	0.9441	0.9097	1.0052	0.9955	0.9864	0.9580	0.8824
	8	1.0056	0.9578	0.9396	0.9449	0.9109	0.9921	0.9866	0.9784	0.9547	0.8832
	10	1.0011	0.9559	0.9391	0.9456	0.9104	0.9801	0.9814	0.9741	0.9534	0.8843

TABLE A3

Absorbed dose per unit air kerma (Gy/Gy) for the **esophagus** in the patients with five different body weights and the phantoms with the weight matching of the patients.

Esophagus	Energy (MeV)	Patients					Phantoms				
		60	70	80	100	130	60	70	80	100	130
	0.01	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.015	0.0012	0.0002	0.0000	0.0000	0.0000	0.0001	0.0001	0.0000	0.0000	0.0000
	0.02	0.0193	0.0031	0.0018	0.0002	0.0003	0.0063	0.0044	0.0032	0.0028	0.0010
	0.03	0.2123	0.0956	0.0658	0.0436	0.0262	0.1220	0.0998	0.0850	0.0684	0.0362
	0.04	0.5506	0.3529	0.2574	0.2015	0.1386	0.4001	0.3290	0.3019	0.2537	0.1479
	0.05	0.8611	0.6086	0.4679	0.3995	0.3053	0.7035	0.6063	0.5647	0.4727	0.3041
	0.06	1.0487	0.8120	0.6461	0.5671	0.4501	0.9375	0.8155	0.7716	0.6743	0.4545
	0.07	1.1071	0.8970	0.7410	0.6447	0.5270	1.0411	0.9462	0.8939	0.7859	0.5464
	0.08	1.1092	0.9258	0.7981	0.6969	0.5823	1.0725	0.9970	0.9570	0.8370	0.6212
	0.1	1.0683	0.9398	0.7749	0.7006	0.6039	1.0986	0.9991	0.9774	0.8778	0.6492
	0.2	0.9217	0.8057	0.7171	0.6412	0.5768	0.9538	0.9058	0.8870	0.8114	0.6304
	0.3	0.9030	0.7812	0.6981	0.6416	0.5721	0.9151	0.8771	0.8532	0.7875	0.6306
	0.4	0.8888	0.7656	0.7106	0.6457	0.5804	0.8962	0.8646	0.8426	0.7817	0.6143
	0.5	0.8887	0.7644	0.7086	0.6589	0.6049	0.8885	0.8564	0.8374	0.7780	0.6304

Esophagus Energy (MeV)	Patients					Phantoms				
	60	70	80	100	130	60	70	80	100	130
0.6	0.8864	0.7686	0.7386	0.6691	0.6163	0.8838	0.8672	0.8364	0.7899	0.6500
0.8	0.8951	0.7814	0.7438	0.6938	0.6398	0.8898	0.8682	0.8500	0.8046	0.6751
1	0.9069	0.7987	0.7666	0.7205	0.6730	0.8952	0.8753	0.8580	0.8131	0.6932
2	0.9138	0.8294	0.8196	0.7774	0.7518	0.9312	0.9033	0.8813	0.8530	0.7563
3	0.9368	0.8585	0.8536	0.8109	0.7910	0.9404	0.9265	0.9030	0.8837	0.7919
4	0.9473	0.8689	0.8691	0.8362	0.8099	0.9453	0.9312	0.9180	0.9137	0.8055
5	0.9437	0.8730	0.8734	0.8428	0.8210	0.9340	0.9373	0.9233	0.9112	0.8242
6	0.9458	0.8697	0.8764	0.8495	0.8270	0.9422	0.9424	0.9327	0.9137	0.8287
8	0.9457	0.8703	0.8784	0.8552	0.8293	0.9364	0.9382	0.9326	0.9160	0.8382
10	0.9390	0.8695	0.8753	0.8596	0.8311	0.9319	0.9223	0.9232	0.9058	0.8427

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Fig. 1.

The depth of esophagus from the frontal body surface at different level of vertebrae from the 7th cervical vertebrae (C7) down to Gastro-Esophageal Junction (GE) for the five patients with the weight of 60, 70, 80, 100, and 130 kg.

Fig. 2. Comparison of organ dose coefficients (Gy/Gy) for (a) lungs, (b) heart, and (c) esophagus for the body weight of 60, 70, 80, 100, and 130 kg between five adult male patient models and five body size-dependent phantoms.

Fig. 3.

Comparison of absolute percent difference (%) for the lungs, heart, and esophagus between the patient-specific dose coefficients and two sets of phantom-based dose coefficients: ICRP 74 reference phantom and body size-dependent phantoms.

TABLE I

Mass (g) of the lungs, esophagus, and heart for the patients with the weight of 60, 70, 80, 100, and 130 kg and the phantoms corresponding to the weights.

Organs	Body Weight (Kg)				
	Patient 60	Patient 70	Patient 80	Patient 100	Patient 130
Lungs	1223	1519	1340	2006	1750
Esophagus	18	19	33	38	25
Heart	770	642	1061	976	983
<hr/>					
	Phantom 60	Phantom 70	Phantom 80	Phantom 100	Phantom 130
Lungs	852	962	1224	1222	1239
Esophagus	27	31	39	39	40
Heart	563	636	807	808	820

Percent difference (%) between patient-specific organ dose and (1) the reference phantom-based dose (top) and (2) the body size- dependent phantom-based dose (bottom) at the photon energy of 0.08MeV. percent difference = $\frac{\text{phantom dose}-\text{patient dose}}{\text{patient dose}} \times 100$.

TABLE II

Organs	Reference size phantom				
	Patient 60	Patient 70	Patient 80	Patient 100	Patient 130
Lungs	-2	-4	-26	-5	-29
Heart	7	-9	-17	-24	-30
Esophagus	-7	-22	-33	-41	-51

Organs	Body size-dependent phantoms				
	Patient 60	Patient 70	Patient 80	Patient 100	Patient 130
Lungs	4	2	30	-10	-16
Heart	-8	5	12	8	-18
Esophagus	-3	8	20	20	7