Monte Carlo calculation of imaging doses from diagnostic multidetector CT and kilovoltage cone-beam CT as part of prostate cancer treatment plans

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Purpose: To calculate imaging doses to the rectum, bladder, and femoral heads as part of a prostate cancer treatment plans, assuming an image guided radiation therapy (IGRT) procedure involving either the multidetector CT (MDCT) or kilovoltage cone-beam CT (kV CBCT).

Methods: This study considered an IGRT treatment plan for a prostate carcinoma patient involving 50.4 Gy from 28 initial fractions and a boost of 28.8 Gy from 16 fractions. A total of 45 CT imaging procedures, each involving a MDCT or a kV CBCT scan procedure, were carefully modeled using the MCNPX code version 2.5.0. The MDCT scanner model is based on the GE LightSpeed 16-MDCT scanner and the kV CBCT scanner model is based on the Varian On-Board Imager using parameters reported by the CT manufacturers and literatures. A patient-specific treatment planning CT data set was used to construct the phantom for the dose calculation. The target, organs-at-risk (OARs), and background voxels in the CT data set were categorized into six tissue types according to CT numbers for Monte Carlo calculations.

Results: For a total of 45 imaging procedures, it was found that the rectum received 78.4 and 76.7 cGy from MDCT and kV CBCT, respectively. The bladder received slightly greater doses of 82.4 and 77.9 cGy, while the femoral heads received much higher doses of 182.3 and 141.3 cGy from MDCT and kV CBCT, respectively. To investigate the impact of these imaging doses on treatment planning, OAR doses from MDCT or kV CBCT imaging procedures were added to the corresponding dose matrix reported by the original treatment plans to construct dose volume histograms. It was found that after the imaging dose is added, the rectum volumes irradiated to 75 and 70 Gy increased from 13.9% and 21.2%, respectively, in the original plan to 14.8% and 21.8%. The bladder volumes receiving 80 Gy increased to 4.6% from 4.1% in the original plan and the volume receiving 75 Gy increased to 7.9% from 7.5%. All values remained within the tolerance levels: $V_{70} < 25\%$, $V_{75} < 15\%$ for rectum and $V_{75} < 25\%$, $V_{80} < 15\%$ for bladder. The irradiation of femoral heads was also acceptable with no volume receiving >45 Gy.

Conclusions: IGRT procedures can irradiate the OARs to an imaging dose level that is great enough to require careful evaluation and perhaps even adjustment of original treatment planning in order to still satisfy the dose constraints. This study only considered one patient CT because the CT x rays cover a relatively larger volume of the body and the dose distribution is considerably more uniform than those associated with the therapeutic beams. As a result, the dose to an organ from CT imaging doses does not vary much from one patient to the other for the same CT settings. One factor that would potentially affect such CT dose level is the size of the patient body. More studies are needed to develop accurate and convenient methods of accounting for the imaging doses as part of treatment planning. © 2010 American Association of Physicists in Medicine.

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I. INTRODUCTION

Image guided radiation therapy (IGRT) treatment utilizes intrafractional and interfractional imaging procedures to iden-

tify and localize the target and organs-at-risk (OARs). During the whole course of the treatment, computed tomography (CT)-on-rails using diagnostic multidetector computed tomography (MDCT) or kilovoltage cone-beam CT (kV

CBCT) mounted on a linear accelerator is used repeatedly to offer three-dimensional (3D) volumetric anatomical information for patient setup, assessing intrafractional organ motion and tumor volume variations.^{1,2} In most cases, a CT scan of the patient is performed initially to develop a treatment plan that will be delivered without any adjustment to account for radiation doses from IGRT imaging procedures.

Given the increasingly widespread usage of x-ray CT in IGRT, it is not surprising that the so-called “imaging dose” to the surrounding healthy tissues may be elevated to a level that can no longer be ignored in the treatment planning. To provide a guidance to the medical physics community about the emerging issues related to the imaging dose, the American Association of Physicists in Medicine formed the Task Group 75 (AAPM TG-75) to make a number of recommendations on how to estimate and manage radiation exposure to the patient.³ The International Commission on Radiological Protection Report 102 also emphasized that it is important to manage the patient dose during multiple MDCT scan.⁴ Several research groups have also reported methods to estimate imaging doses to various organs using either computational or experimental approaches.^{5–12} For example, Wen *et al.*⁵ reported that the cumulative kV CBCT dose to the pelvic bones was 4 Gy for a prostate treatment involving 42 fractions. Ding *et al.*⁷ found that the kV CBCT procedure irradiated the bone to a dose level that was up to a factor of 4 higher than that to the surrounding soft tissue. Using a whole-body computational phantom and a detailed kV CBCT scanner model, doses to as many as 100 organs and the effective dose were reported by Gu *et al.*¹¹

More recent studies by Ding *et al.*¹⁰ and Alaei *et al.*¹³ represent a new effort to possibly include imaging doses in existing radiation treatment planning (RTP) systems. For a CT scanner that is normally operated at 140 keV, however, the radiation interaction characteristics are quite different from those of the megavoltage beams modeled in the RTPs. The conventional dose calculation algorithms (pencil beam, superposition, or convolution algorithms) employed in commercial RTP systems were based on energy deposition kernels in water and density scaling theorem. Such methods work well for megavoltage x rays but do poorly in the kilovoltage energies. As a result, dose to the bone from kilovoltage x rays may be significantly underestimated by the existing RTP systems and correction factors have been suggested.¹³ To date, there is no study that aims to compare the imaging doses in the context of treatment planning involving various dose constraints. Such a study would require the usage of Monte Carlo methods that can provide accurate voxel-by-voxel dose distributions inside a patient-specific anatomy.

This paper describes a project to calculate imaging dose to the rectum, bladder, and femoral heads for a prostate cancer treatment case using hypothetical IGRT procedures involving either MDCT and kV CBCT imaging modalities. Models of the patient anatomy and CT scanners were carefully defined in a Monte Carlo code for radiation transport and dose calculations. The imaging doses are derived and analyzed and the impact on treatment plans is then analyzed

by comparing voxel-based dose volume histograms (DVHs) against various treatment planning criteria. The data provided by this project are based on actual patient anatomy and a clinical treatment plan and this work is the first time to use the patient CT anatomy and the clinical treatment plan for the same patient to re-evaluate the plan by taking into account of the imaging dose; thus the results offer useful information to the medical physics community, including the newly formed AAPM TG-180 that is charged with the task of evaluating the possibility of accounting for imaging doses in RTP.

II. MATERIALS AND METHODS

II.A. Case study: A patient-specific prostate cancer treatment plan

One treatment plan for a prostate carcinoma patient was selected for this project. The plan was optimized using the Corvus treatment planning system (TPS) (Corvus, Nomos Corp., Sewickley, PA). According to the radiation therapy oncology group 0126 protocol, clinical target volume was prescribed 50.4 Gy in 28 fractions, followed by a 28.8 Gy boost to the gross tumor volume (GTV) in 16 fractions. The planning target volume (PTV) was obtained by expanding the GTV by 5 mm in all directions. The dose constraints to OARs are: For the rectum, the percentage volumes of receiving the prescription dose 75 (V_{75}) and 70 Gy (V_{70}) were less than 15% ($V_{75} < 15\%$) and 25% ($V_{70} < 25\%$), respectively; for the bladder, $V_{80} < 15\%$ and $V_{75} < 25\%$; and for the femoral heads, no volume should exceed 45 Gy. In this study, a total of 45 imaging procedures (including the extra initial one CT procedure for staging and original planning) were considered as a typical case scenario involving the usage of either a MDCT or a kV CBCT scanner for the daily patient treatment setup.

II.B. Patient anatomical model

A set of planning CT images, with contours of the tumor target (prostate) and OARs (rectum, bladder, and femoral heads) contoured by a radiation oncologist, as visualized in Fig. 1 using the CERR software (Computational Environment for Radiotherapy Research, Washington University, St. Louis, MO), was used to construct a voxelized patient anatomical model for Monte Carlo dose calculations. Voxels belonging to the prostate or OARs were carefully defined in each slice of the CT data set based on the organ contours information in the treatment file. Voxels outside these contoured organs were specified as one of six tissue types (the lung, fat, water, soft tissues, bone, and air) according to their CT numbers using the 3D-DOCTOR v.4.0 software (Able Software Corp., Lexington, MA). Using a total of 120 CT slices, each CT slice at 2.5 mm thickness, a 3D patient-specific model was created and visualized in Fig. 2.

II.C. CT scanner model

Both the MDCT and kV CBCT scanner models, previously developed,^{11,14} were adopted for this project. The

FIG. 1. CT data set from a prostate carcinoma patient with organ structure contours is viewed using CERR software. All of 120 CT slices are shown in the left panel and organ contours are displayed using orthogonal planar views on the transverse (middle panel), sagittal, and coronal window (right panel).

MDCT model used in this project was for a GE LightSpeed 16-MDCT scanner (General Electric Healthcare Corporation, Waukesha, WI) consisting of 16 rows of 0.625 mm wide detectors and eight rows of 1.25 mm detectors. The following x-ray beam collimation options were considered in the modeling (given in the format of $N \times T$, where N represents the number of data channels and T is the nominal width of each data channel): 16×0.625 mm (8×1.25 mm) and 16×1.25 mm (8×2.5 mm), as well as 2×0.625 and 1×5 mm modes. The scanner can operate under axial or helical modes, supporting tube voltages of 80, 100, 120, and 140 kVp.

In our case study, the CT scan protocol was as follows: Collimation of 20 mm (16×1.25 or 8×2.5 mm), 250 mAs per rotation, 120 kVp beam, and helical mode with a pitch of 1.375. For the MDCT scan, a total of 120 slices, each at 2.5 mm thickness, covering 30 cm of the patient body were assumed for this study. If the imaging volume is larger, additional organs will be exposed, although the OARs will only slightly increase due to scattering from slices away from

FIG. 2. 3D rendering of patient anatomy from outlined and segmented volumetric CT image data set.

FIG. 3. MDCT scanner modeling (a) a point at the location of the anode of the x-ray tube, the flat filter, the bow-tie filter, and the beam shape are defined. The CTDI phantom was used to validate the modeled MDCT scanner. (b) The energy spectrum simulated by XCOMP5R.

OARs. If the imaging volume is smaller, there is a chance that some of the OARs may be partially exposed and the dose will be slightly reduced due to less scattering.

Figure 3 shows the specific geometries for the CT x-ray beam and x-ray energy spectrum. The shapes are further refined through trial-and-error manner using measured and calculated computed tomography dose index (CTDI) values as described previously.¹² Aluminum was selected as the material for the bowtie filter. The software XCOMP5R (Ref. 15) was used to simulate the x-ray energy spectrum for CT scanner modeling as illustrated in Fig. 3(b).

The kV CBCT scanner model was based on the Varian on-board imager of the Varian Trilogy (Varian Medical System, Palo Alto, CA). Compared to fan-shaped x-ray beam for the diagnostic CT,¹⁴ the CBCT beam follows a pyramid-shaped fan with a large angle to cover necessary volume. The parameters for the CBCT scanner were adopted from those reported by the CT manufacturers and found in the literatures. Two scan modes, half-fan scan and full-fan scan were considered. Correspondingly, a half-fan bow-tie filter and a full-fan bow-tie filter were also modeled as described in detail in a previous study.¹⁶ Using measured and simulated central dose values, a conversion factor was derived to convert all the simulated dose values in the unit of MeV/g per particle into the dose values in the unit of mGy/mAs. The de-

FIG. 4. Detailed kV CBCT geometric model: Half-fan scan mode, $X_1 = 8.3$ cm, and $X_2 = 24.9$ cm.

tailed steps for modeling MDCT, kV CBCT, and experimental validations have been described in our previous papers.^{11,14}

In this study, the following kV CBCT scan protocol was adopted for this study: A half-fan mode with a half bow-tie filter is used involving 125 kVp beam and 250 mA s per rotation (for the low-dose mode); the clinical default X-Y blades settings are $X_1 = 8.3$ cm, $X_2 = 24.9$ cm, and $Y_1 = Y_2 = 11.8$ cm for half-fan scan mode at 100 cm source-to-surface distance, respectively. The geometry of the kV CBCT scanner model is shown in Fig. 4. The volume covered in z direction was controlled by the Y blades setting. In this study, the range covered in the z direction is 23.6 cm (i.e., $Y_1 + Y_2$) and all the OARs and target organ were fully covered during the kV CBCT scan. The effect of the scanning volume is similar to that for the MDCT discussed earlier.

II.D. Monte Carlo dose calculations

To calculate patient doses from a CT imaging procedure, the patient and CT scanner models were defined using the Monte Carlo N-Particle extended (MCNPX) v2.5.0 code.¹⁷ The cookie-cutter cell function of MCNPX was used to specify the CT x-ray beam size and shape. The phantom derived from patient CT data was implemented into MCNPX using an in-house software¹⁸ that converted CT numbers to the MCNPX geometry definition input file. The voxel size in the original TPS file was $0.977 \times 0.977 \times 2.5$ mm. In the Monte Carlo simulation, due to the memory usage and MCNPX limit on number of voxel, two original voxels were combined into one and the combination rule was also recorded in the log

TABLE I. Imaging doses (assuming a total of 45 scans) from MDCT and kV CBCT at 250 mAs/scan.

Sensitive organ	Mean dose (per scan)		Mean dose (45 scans)	
	MDCT (cGy)	kV CBCT (cGy)	MDCT (cGy)	kV CBCT (cGy)
Rectum	1.74	1.71	78.4	76.7
Prostate	1.41	1.41	63.5	63.5
Bladder	1.83	1.73	82.4	77.9
Left femoral head	4.05	3.14	182.3	141.3

file. So the voxel size used in Monte Carlo simulations was $1.954 \times 1.954 \times 5$ mm. The x-ray energy spectrum simulated by XCOMPSR as shown in Fig. 3(b) was used in the Monte Carlo dose calculations. Absorbed doses to voxels of interest were recorded by the tally card type 6 (F6: P) in the MCNPX code using the “Repeated Structure” format. The raw dose results were then converted into the patient dose values using the conversion factor as described previously.¹⁴ The imaging and treatment dose were finally added together at the voxel level.

All simulations in this project were run on a Linux server computer with two quad-core Intel Xeon central processing units and 8 GB random-access memory. A typical run took a few hours to yield statistically acceptable voxel dose results without any effort on acceleration.

III. RESULTS AND DISCUSSION

Table I summarizes the doses to the OARs derived from Monte Carlo simulations using MDCT and kV CBCT scanner models. For a total of 45 scans, the rectum mean absorbed dose was found to be 78.4 and 76.7 cGy from MDCT and kV CBCT, respectively. The bladder received slightly greater doses, 82.4 and 77.9 cGy, while the femoral heads received much higher doses, 182.3 and 141.3 cGy, from MDCT and kV CBCT, respectively. Since the x-ray tube current was assumed to be 250 mAs for both scanners, the dose calculation results are similar as expected. The results confirm that given the same tube current setting, the CT scanners (MDCT and kV CBCT) would lead to similar dose outcomes. Although these OAR doses are relatively low compared to the target doses delivered during the radiation therapy, they are clearly not negligible. In fact, these OAR doses may change dosimetric parameters of the treatment plan. Figure 5 shows the imaging doses from the MDCT and kV CBCT procedures also plotted in terms of DVHs. All imaging DVHs have a very steep shoulder, suggesting that the imaging doses are distributed uniformly in each organ, albeit at the relatively lower dose level than that in the original DVHs provided by a RTP system.

To further investigate the effect of imaging doses on treatment planning, DVHs for the MDCT imaging doses are added to the corresponding dose matrix in the original treatment plans using data extracted from the CERR software. The comparison is illustrated in two figures. In Fig. 6(a), the original treatment plans without and with imaging doses are

FIG. 5. Patient imaging dose DVHs from 45 MDCT (in solid line) and from kV CBCT scans (in marker line) showing steep shoulders for a relatively low but uniform dose distributions in each organ.

compared in terms of DVHs. As can be seen, the dose constraints for the rectum at 75 ($V_{75} < 15\%$) and 70 Gy ($V_{70} < 25\%$) are satisfied, showing actually fractional volumes of 13.9% and 21.2%, respectively. After the imaging doses from MDCT or kV CBCT are added, however, the values for the rectum are increased to 14.8% and 21.75% for MDCT and 14.82% and 21.84% for kV CBCT, respectively. For the bladder, with the dose constraints at 75 ($V_{75} < 25\%$) and 80 Gy ($V_{80} < 15\%$), after adding the imaging doses, the values are increased to 4.61% for MDCT and 4.58% for kV CBCT from 4.1% at 80 Gy ($V_{80} < 15\%$) and to 7.9% for MDCT and kV CBCT from 7.5% at 75 Gy ($V_{75} < 25\%$). The dose constraints for the rectum and the bladder are still satisfied. The femoral heads are also acceptable with no volume > 45 Gy, although the imaging dose level is relatively high.

In other previous studies, the doses reported by Wen *et al.*⁵ were based on the data measured by thermoluminescent dosimeters. Alaei *et al.*¹³ reported doses from the kV CBCT procedure using a Rando physical phantom. Both experimental methods suffer from a well known difficulty in accurately placing a dosimeter in various parts of the body, especially near bones and surrounding soft tissues. In this study, patient-specific CT images and Monte Carlo calculations have the advantage of providing a more precise and detailed dose distributions than the previous measured results.

It must be noted here that although imaging dose from this study did not compromise the original treatment plans, the results suggest that it is prudent to leave adequate dose margin in an IGRT treatment plan to accommodate for potential imaging doses. Furthermore, IGRT protocols different from those reported in this study can cause the imaging dose to be still higher when, for example, a greater tube current or scanning volume is employed.¹¹ In the prostate case reported here, the dose to the rectum and femoral heads require particular attention and, therefore, stricter planning criteria may

FIG. 6. Comparison of DVHs without and with MDCT imaging doses (45 scans): (a) DVHs without imaging doses (in solid lines) showing that the dose constraints for the rectum at 75 ($V_{75} < 15\%$) and 70 Gy ($V_{70} < 25\%$) are satisfied showing actually fractional volumes of 13.9% and 21.2%, respectively. When the imaging doses from MDCT are included (in dashed lines), the rectum volumes are increased to 14.8% and 21.8%, still satisfactory. (b) A zoomed-in view of the DVHs highlighting the shifts due to imaging doses (kV CBCT results following a similar trend).

be necessary when an IGRT procedure is involved. As Fig. 6(b) shows, adding imaging doses results in a nearly uniform shift of the planned DVH curves by as much as the organ-average imaging dose. This suggests that planning criteria for IGRT may be adjusted according to dose levels reported in this study, corrected for specific scanning parameters. To illustrate this point, in our case, with the mean rectum dose of 0.8 Gy from 45 scans, one may want to require that $V_{74.2} < 25\%$ in the original plan (i.e., the constraint dose is reduced by 0.8 Gy expected from imaging procedures) to ensure that V_{75} does not exceed 25%. Such precise imaging dose data may be used as an “imaging dose margin” in the IGRT treatment plan instead of trying to use the RTP system to report such doses.

IV. CONCLUSIONS

Monte Carlo study of MDCT and kV CBCT procedures for a patient-specific anatomical model was performed in this project to investigate the effects of imaging doses on treatment plans. Imaging doses to OARs, expressed in DVHs, were compared to the original treatment plans at the voxel level. The results suggest that imaging doses from typical IGRT procedures are at a level that may require the original plan to be carefully re-evaluated and even adjusted in order to still satisfy the dose constraints imposed on the OARs. Since simplified dose calculation methods in RTP systems are not suitable for low-energy x rays involving bones and lungs,⁶ Monte Carlo calculations such as reported in this paper offer useful data for comparison and potential improvement in IGRT treatment planning.

This study only considered one patient CT because it is known that the CT x rays cover a relatively large volume of the body, including PTV and OARs, and the dose distribution is considerably more uniform than those associated with the therapeutic beams. As a result, dose to an organ from CT imaging does not vary much from one patient to the other for the same CT settings. A factor that would potentially affect such CT dose level is the size of the patient body. To understand the degree of such effect, we have considered data derived from a deformable patient phantom that has a body-weight representing the 5th–95th percentile of the American population.¹⁹ Using this size-varied patient phantom, we have estimated that the organ doses would vary by 10%–20%. This estimate provides a range of body-size caused imaging dose difference for the American population. It is clear that more studies are needed to develop accurate yet convenient methods of accounting for the imaging doses as part of treatment planning for IGRT.

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¹ X. D. Zhang, L. Dong, A. K. Lee, J. D. Cox, D. A. Kuban, R. X. Zhu, X. C. Wang, Y. P. Li, W. D. Newhauser, M. Gillin, and R. Mohan, "Effect of anatomic motion on proton therapy dose distributions in prostate cancer

treatment," *Int. J. Radiat. Oncol., Biol., Phys.* **67**, 620–629 (2007).

- ² J. R. Wong, L. Grimm, M. Uematsu, R. Oren, C. W. Cheng, S. Merrick, and P. Schiff, "Image-guided radiotherapy for prostate cancer by CT-linear accelerator combination: Prostate movements and dosimetric considerations," *Int. J. Radiat. Oncol., Biol., Phys.* **61**, 561–569 (2005).
- ³ M. J. Murphy, J. Balter, S. Balter, J. A. BenComo, I. J. Das, S. B. Jiang, C. M. Ma, G. H. Olivera, R. F. Rodebaugh, K. J. Ruchala, H. Shirato, and F. F. Yin, "The management of imaging dose during image-guided radiotherapy: Report of the AAPM Task Group 75," *Med. Phys.* **34**, 4041–4063 (2007).
- ⁴ ICRP-102, "Managing patient dose in multi-detector computed tomography (MDCT)," *Ann. ICRP* **37**, 1–79 (2007).
- ⁵ N. Wen, H. Guan, R. Hammoud, D. Pradhan, T. Nurusev, S. Li, and B. Movsas, "Dose delivered from Varian's CBCT to patients receiving IMRT for prostate cancer," *Phys. Med. Biol.* **52**, 2267–2276 (2007).
- ⁶ G. X. Ding, D. M. Duggan, and C. W. Coffey, "Characteristics of kilovoltage x-ray beams used for cone-beam computed tomography in radiation therapy," *Phys. Med. Biol.* **52**, 1595–1615 (2007).
- ⁷ G. X. Ding, D. M. Duggan, and C. W. Coffey, "Accurate patient dosimetry of kilovoltage cone-beam CT in radiation therapy," *Med. Phys.* **35**, 1135–1144 (2008).
- ⁸ M. K. Islam, T. G. Purdie, B. D. Norrlinger, H. Alasti, D. J. Moseley, M. B. Sharpe, J. H. Siewerdsen, and D. A. Jaffray, "Patient dose from kilovoltage cone beam computed tomography imaging in radiation therapy," *Med. Phys.* **33**, 1573–1582 (2006).
- ⁹ G. X. Ding and C. W. Coffey, "Radiation dose from kilovoltage cone beam computed tomography in an image-guided radiotherapy procedure," *Int. J. Radiat. Oncol., Biol., Phys.* **73**, 610–617 (2009).
- ¹⁰ G. X. Ding, J. M. Pawlowski, and C. W. Coffey, "A correction-based dose calculation algorithm for kilovoltage x rays," *Med. Phys.* **35**, 5312–5316 (2008).
- ¹¹ J. W. Gu, B. Bednarz, X. G. Xu, and S. B. Jiang, "Assessment of patient organ doses and effective doses using the VIP-man adult male phantom for selected cone-beam CT imaging procedures during image guided radiation therapy," *Radiat. Prot. Dosim.* **131**, 431–443 (2008).
- ¹² S. Kim, T. T. Yoshizumi, G. Toncheva, S. Yoo, and F. F. Yin, "Comparison of radiation doses between cone beam CT and multi detector CT: TLD measurements," *Radiat. Prot. Dosim.* **132**(3), 339–345 (2008).
- ¹³ P. Alaei, G. X. Ding, and H. Q. Hu, "Inclusion of the dose from kilovoltage cone beam CT in the radiation therapy treatment plans," *Med. Phys.* **37**(1), 244–248 (2010).
- ¹⁴ J. W. Gu, B. Bednarz, P. F. Caracappa, and X. G. Xu, "The development, validation and application of a multi-detector CT (MDCT) scanner model for assessing organ doses to the pregnant patient and her fetus using Monte Carlo methods," *Phys. Med. Biol.* **54**, 2699–2717 (2009).
- ¹⁵ R. Nowotny and A. Höfer, "Ein Programm für die Berechnung von diagnostischen Röntgenspektren," *Fortschr. Röntgenstr.* **142**(6), 685–689 (1985).
- ¹⁶ X. G. Xu, J. W. Gu, and W. Song, "Monte Carlo based kV CBCT modeling and dose calculations involving anatomical phantom," *Med. Phys.* **36**(6), 2813–2813 (2009).
- ¹⁷ D. B. Pelowitz, *MCNPX User's Manual Version 2.5.0* (Los Alamos National Laboratory, Los Alamos, 2005).
- ¹⁸ A. P. Ding, J. W. Gu, P. F. Caracappa, and X. G. Xu, "Development and testing of a CT dose software 'VirtualDose' using anatomically realistic patient phantoms: Preliminary results for the Phase I of the project," *Med. Phys.* **37**(6), 3463–3463 (2010).
- ¹⁹ Y. H. Na, B. Q. Zhang, J. Y. Zhang, P. F. Caracappa, and X. G. Xu, "Deformable adult human phantoms for radiation protection dosimetry: Anthropometric data representing size distributions of adult worker populations and software algorithms," *Phys. Med. Biol.* **55**, 3789–3811 (2010).