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Extension of RPI-adult male and female computational phantoms to obese patients and a Monte Carlo study of the effect on CT imaging dose

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Abstract

Although it is known that obesity has a profound effect on x-ray computed tomography (CT) image quality and patient organ dose, quantitative data describing this relationship are not currently available. This study examines the effect of obesity on the calculated radiation dose to organs and tissues from CT using newly developed phantoms representing overweight and obese patients. These phantoms were derived from the previously developed RPI-adult male and female computational phantoms. The result was a set of ten phantoms (five males, five females) with body mass indexes ranging from 23.5 (normal body weight) to 46.4 kg m⁻² (morbidly obese). The phantoms were modeled using triangular mesh geometry and include specified amounts of the subcutaneous adipose tissue and visceral adipose tissue. The mesh-based phantoms were then voxelized and defined in the Monte Carlo *N*-Particle Extended code to calculate organ doses from CT imaging. Chest–abdomen–pelvis scanning protocols for a GE LightSpeed 16 scanner operating at 120 and 140 kVp were considered. It was found that for the same scanner operating parameters, radiation doses to organs deep in the abdomen (e.g., colon) can be up to 59% smaller for obese individuals compared to those of normal body weight. This effect was found to be less significant for shallow organs. On the other hand, increasing the tube potential from 120 to 140 kVp for the same obese individual resulted in increased organ doses by as much as 56% for organs within the scan field (e.g., stomach) and 62% for those out of the scan field (e.g., thyroid), respectively. As higher tube currents are often used for larger patients to maintain image quality, it was of interest to quantify the associated effective dose. It was found from this study that when the mAs was doubled for the obese level-I, obese level-II and morbidly-obese phantoms, the effective dose relative to that of the normal weight phantom increased by 57%, 42% and 23%, respectively. This set of new obese phantoms can be used in the future to study the optimization of image quality and radiation dose for patients of different weight classifications. Our ultimate goal is to compile all the data derived from these phantoms into a comprehensive dosimetry database defined in the VirtualDose software.

1. Introduction

The prevalence of overweight and obese individuals in the United States has increased markedly over the past 20 years. A recent survey by the National Health and Nutrition Examination Survey (NHANES) estimates that nearly 60% of the adult American population can be diagnosed as being clinically overweight or obese (Flegal *et al* 2010,

Finucane *et al* 2011). Obesity has been linked to a number of diseases such as cardiovascular disease, type 2 diabetes and even some types of cancer (Haslam and James 2005). Given this alarming trend and the health risks associated with obesity, it is not surprising that such individuals represent an increasingly important fraction of patients entering radiology clinics. X-ray computed tomography (CT) imaging of overweight and obese patients poses a unique challenge because their body size requires the use of special protocols to ensure diagnostic image quality. Typical protocol changes include increasing the field of view, tube potential and/or tube current. In extreme cases, a large-bore scanner may be required to accommodate patients who exceed the ~70 cm patient port diameter typical of most commercial scanners (Modica *et al* 2011). In general, the net consequence of these protocol changes is that, compared to normal-weight patients, obese patients face a potentially greater radiation risk due to the higher CT exposures they receive.

Although obese patients are common in radiology clinics, radiation dosimetry research involving such patients has been sparse in the literature. More than 100 computational human phantoms for radiation dose calculations have been reported (Xu and Eckerman 2009, Na *et al* 2010, Cassola *et al* 2011), but they largely represent only the average or standard individuals as defined by the International Commission on Radiological Protection (ICRP), ignoring large segments of the population such as obese individuals. Reporting one of the few studies on obese patient radiation dose, Yanch *et al* (2009) estimated the radiation dose to overweight and obese patients from radiographic examinations. In their study, stylized male and female computational phantoms were modified to simulate the effect of subcutaneous fat on patient radiation dose. Layers of adipose tissue up to 30 cm thick were added to the normal weight computational phantoms in the anterior, lateral and posterior regions of the torso. A 12 cm diameter air-filled detector was then positioned 5 cm behind the simulated patient to calculate the exit dose. The results showed that for a constant exit dose the effective dose to the patient from the radiographic examinations increased with body thickness. In particular, for 120 kVp chest radiographs, Yanch *et al* found that the effective dose for obese phantoms increased by factors of 2–31 for males and 2–45 for females depending on the fat distribution and the orientation of the phantoms in the x-ray beam. Similarly, for 80 kVp abdomen radiographs the effective dose enhancement factors ranged from 2 to 83 for males and 2 to 76 for females (Yanch *et al* 2009). While this study was an important effort in considering fat distribution in computational phantoms, the use of stylized phantoms oversimplifies the anatomy by approximating organ shapes with simple surface defined as first, second, or fourth degree polynomials. The lack of realism offered by stylized phantoms may result in significant discrepancies in the calculated organ doses, ranging from a few per cent to over 100% under certain conditions when compared with image-based voxel phantoms (Chao *et al* 2001a, 2001b, Zankl *et al* 2002, Lee *et al* 2006). For instance, a recent CT dosimetry study by Liu *et al* (2010) reported a 25% difference between the calculated dose to stylized and voxel phantoms for organs within the scan range. Another major limitation of this study is that the adipose tissues were only positioned at the surface of the stylized phantom and did not account for fat located deep within the abdomen surrounding the internal organs. Furthermore, Yanch *et al* (2009) did not consider CT imaging which subjects patients to a much higher radiation exposure than conventional radiography.

X-ray CT is one of the most widely used diagnostic medical imaging modalities. Its rise in popularity as a tool for patient evaluation reflects the incremental process by which the technology has improved since its first commercial introduction in the early 1970s (Kalender 2005). State-of-the-art CT scanners can produce three-dimensional images of patient anatomy with sub-millimeter resolution in just a matter of seconds. While CT imaging clearly plays an invaluable role in modern medicine, its rapid adoption has resulted in a dramatic increase in the average medical radiation exposure to the United States

population as highlighted in a 2009 report by the National Council on Radiation Protection (NCRP 2009). This trend in CT usage is worrisome because the risks of cancer induction from the current CT exposure levels, while small and often medically justified, are still not clearly understood (Sodickson *et al* 2009, Berrington de Gonzalez *et al* 2009, Brenner 2010). As CT dosimetry is trending towards more patient-specific approaches (Gu *et al* 2008, Turner *et al* 2011, AAPM 2011), improved CT dose estimation and reporting methodology will be important for measuring the success of dose-saving efforts. An ability to quantify organ doses for obese patients as well as for normal individuals is important for designing CT scanning protocols which optimize image quality while appropriately managing the radiation exposure. However, existing tools for CT dose estimates, such as ImPACT CT patient dosimetry calculator (ImPACT 2011), CT-Dose (2011) and CT Expo (Stamm and Nagel 2002), are based on stylized computational human phantoms that do not represent important segments of the population such as pregnant, pediatric, overweight and obese patients.

This paper describes the development of a set of realistic body mass index (BMI)-adjustable male and female computational phantoms and their application to a study of the effect of obesity on the radiation dose from CT examinations. Specifically, we are motivated to compare the CT imaging dose of overweight and obese patients with that of patients of normal body weight. This project builds upon our previous experience in two research areas: (1) deformable phantom modeling using the triangular mesh geometry (Zhang *et al* 2009, Na *et al* 2010) and (2) methods for modeling CT scanners in a Monte Carlo code for estimating patient organ doses (Gu *et al* 2009, Ding *et al* 2010b).

2. Materials and methods

2.1. Anthropometrics of overweight and obesity

BMI is commonly used as a measure of obesity and is calculated as the body mass divided by the square of body height in units of kg m^{-2} (CDC 2009, WHO 2011). The World Health Organization (WHO) defines an individual, regardless of gender, as being clinically overweight if the BMI is 25–29.9 kg m^{-2} , obese if the BMI is 30–39.9 kg m^{-2} and morbidly obese if the BMI exceeds 40 kg m^{-2} (Haslam and James 2005, WHO 2011), as summarized in table 1.

BMI is also closely related to both the body fat percentage and the total body fat (Gray and Fujioka 1991). *In vivo* measurements of body fat distribution can be made using a number of anthropometric methods such as dual-energy x-ray absorptiometry (DXA), magnetic resonance imaging (MRI) and CT (Carroll *et al* 2008, Camhi *et al* 2011). Adipose tissues in the human body can be subdivided into two main classes: (1) subcutaneous adipose tissue (SAT) located beneath the skin and (2) visceral adipose tissue (VAT) which surrounds the abdominal organs (Vanltallie 1998, Smith *et al* 2001, Carroll *et al* 2008, Camhi *et al* 2011). Figure 1 illustrates the division of SAT and VAT on a cross-sectional image of the abdomen in a whole-body tomographic model called VIP-Man (Xu *et al* 2000) developed from color photographs of the National Library of Medicine's (NLM) visible human project data set (<http://www.nlm.nih.gov/research/visible>).

2.2. BMI-adjustable patients modeling

The BMI-adjustable phantoms described in this paper were created by modifying the RPI-adult male (RPI-AM) and RPI-adult female (RPI-AF) phantoms which were previously developed by our group (Zhang *et al* 2009, Na *et al* 2010). These phantoms were derived from the AnatomiumTM three-dimensional (3D) P1 organ mesh dataset (www.anatomium.com) and consist of more than 100 deformable organs defined in the

mesh-geometry format. The weight, height and organ size of RPI-AM and RPI-AF were carefully adjusted to match with reference values defined by the ICRP for average individuals (ICRP 2002).

For adults, the sizes of various internal organs or tissues (except adipose tissues, muscle, or bone) change primarily with age, disease or nutritional status (Heymsfield 2005). Our modeling procedure assumes that the masses of one's internal organs do not change during adulthood. This is a decent approximation for the purpose of radiation protection dosimetry and has been adopted by others (Schindera *et al* 2008, Yanch *et al* 2009, Clark *et al* 2010). Hence, in this study internal organ masses in the RPI-AM and RPI-AF do not change during the BMI-adjustable phantom modeling procedure. One exception is the skin mass which was designed to increase for phantoms with larger BMIs to accommodate the larger skin surface area expected of obese individuals. An interpolation-and-scaling algorithm was developed to automatically generate the new skin surface for each of the obese phantoms as described in our previous work (Liu *et al* 2011).

Figure 2(b) illustrates how the SAT layer was added superficially beneath the skin. The SAT volumes were defined as the region between the body surface and internal body cavity and were adjusted to desired values by scaling the body surface according to anthropometric data from the literature (Smith *et al* 2001, Camhi *et al* 2011). A constant adipose tissue density of 0.92 g cm^{-3} was assigned to the SAT.

As discussed in previous studies by other investigators (Smith *et al* 2001, Carroll *et al* 2008, Ibrahim 2010), VAT is more metabolically active than SAT and of the two categories of fat it is the most strongly correlated with many of the negative health effects often associated with obesity. VAT is not only a major risk factor for some obesity-related diseases but also plays an important role in the study on the effect of adipose tissues on the radiation dose to the deep organs in the abdominal region. No data are readily available which describe how internal organs deform or move due to the presence of excess VAT. Consequently, the same region inside the peritoneal cavity was used to define the VAT volume for all phantoms, regardless of their BMI values (figure 2(a)). The density of this fixed VAT volume was increased proportionally to values greater than 0.92 g cm^{-3} to account for the larger VAT masses expected for obese patients. This modeling method assumes that an artificial increase in the density of VAT will have a similar organ shielding effect as a larger, but more geometrically realistic volume of VAT with the typical adipose density of 0.92 g cm^{-3} . This approximation is deemed suitable because x-ray attenuation depends on the product of density and thickness. A four-step process involving a measurement of the phantom's waist circumference (WC) was adopted to select the VAT density for a particular phantom. In step 1, the phantom's WC was measured at the point midway between the costal margin and iliac crest in the mid-axillary line. In step 2, using a relationship between VAT and WC described in the literature (Camhi *et al* 2011), the VAT areas (cm^2) in the cross-section at the L4–L5 intervertebral disc space were first estimated from the WC measured in step 1. In step 3, the VAT mass was calculated by using the VAT area–mass estimation equation derived from the measurement by Smith *et al* (2001). Lastly, in step 4, the phantom-specific VAT density was calculated by dividing the estimated VAT mass (from step 2) by the fixed VAT volume inside the phantom's peritoneal cavity.

2.3. CT scanner model and scan protocols

A previously developed and validated multi-detector CT (MDCT) scanner model was used in this study (Gu *et al* 2009). The model is based on a GE LightSpeed 16 scanner (General Electric Healthcare Corporation, Waukesha, WI) consisting of 16 rows of 0.625 mm wide detectors as well as 8 rows of 1.25 mm detectors. The MDCT scanner can operate under axial or helical modes, supporting the tube potentials of 80, 100, 120 and 140 kVp. For the

current study, the following helical scan parameters were considered: collimation of 20 mm, 120 kVp and 140 kVp tube potentials in normal weight, overweight and obese phantoms and a pitch of 1.375.

As the effect of adipose tissue on CT imaging dose will be the largest in the torso of the patient, a chest-abdomen-pelvis (CAP) scanning protocol was simulated for each of the BMI-adjustable phantoms. The scan range was chosen to cover the phantoms from just above the clavicles to the mid-iliac crest. The scan lengths for the RPI BMI-adjustable male and female phantoms were 44 and 41 cm, respectively.

2.4. Monte Carlo organ dose calculations

In this study, all CT dose calculations were performed using the Monte Carlo *N*-Particle Extended (MCNPX) code version 2.6.0 (Pelowitz 2005). MCNPX currently does not have the capability of handling polygonal mesh geometries. Consequently, an in-house software was developed to convert the BMI-adjustable phantom mesh geometries into a voxel description using MCNPX's 'repeated structures' format. The voxel size was set to be $3.5 \times 3.5 \times 3.5 \text{ mm}^3$ to avoid exceeding the maximum number of voxels that the MCNPX is able to handle. The default MCNPX photon physics settings and energy cutoffs were used. The F6 track length tally in MCNPX was employed to record the collision kerma as an approximation of the averaged absorbed dose to each organ. For CT dose calculations this is a good approximation because all simulated photons have relatively low energies ($\leq 140 \text{ keV}$ in this study) and the secondary electrons will deposit their energy locally. The dose results reported by MCNPX are in units of $\text{MeV g}^{-1}/\text{source particle}$ and previously determined conversion factors are adopted to convert these data into units of mGy per integrated tube current time of 100 mAs (Gu *et al* 2009).

Effective dose (E) can be used to facilitate the estimation and comparison of the radiation-induced stochastic effects on the whole body (ICRP 2007). Mathematically, E is calculated as a weighted average of the equivalent doses to selected body organs or tissues according to

$$E = \sum_T w_T H_T = \sum_T w_T \sum_R w_R D_{T,R}, \quad (1)$$

where $D_{T,R}$ is the average absorbed dose in a selected organ or tissue T involving the radiation type R , w_R is the radiation weighting factor for the radiation type R and w_T is an organ or tissue weighting factor for the organ or tissue T . This study uses the tissue weighting factors most recently recommended in ICRP Publication 103 (ICRP 2007). In addition, we adopt the ICRP 103 definition of the effective dose as being a sex-averaged value using the equation

$$E = \sum_T w_T \left[\frac{H_T^F + H_T^M}{2} \right], \quad (2)$$

where H_T^F and H_T^M are the equivalent doses for organ or tissue T of the female and male phantoms, respectively.

All simulations were run on a Linux server with 2 quad-core Intel Xeon CPUs and 8GB RAM memory. The specific number of photons in each run was chosen so that the calculated organ dose results had an acceptable level of statistical uncertainty (relative errors $< 1\%$ for most organs and $< 5\%$ for organs with very small volumes located at large distances from the primary beam).

3. Results and discussion

3.1. BMI-adjustable male and female phantoms

In this study, a total of ten new phantoms with different BMI values were developed as an extension of the previously developed RPI-AM and AF Phantoms. Additional phantoms can be easily produced using automatic morphing algorithms that we developed which interpolate between mesh phantoms with different BMI values.

Tables 2 and 3 summarize a few important characteristics of the newly developed BMI-adjustable male and female phantoms which have the weight classifications of normal-weight (NW), over-weight (OW), obese level-I (OI), obese level-II (OII) and morbidly obese (MO). Each phantom is assigned a unique name according to its gender and weight classification: RPI-AM_{NW}, RPI-AM_{OW}, RPI-AM_{OI}, RPI-AM_{OII}, RPI-AM_{MO} and RPI-AF_{NW}, RPI-AF_{OW}, RPI-AF_{OI}, RPI-AF_{OII}, RPI-AF_{MO}. As demonstrated in one of our previous studies (Hegenbart *et al* 2008), different female breast cup sizes can be modeled independent of female total body weight. While not the focus of this study, different breast cup sizes for the RPI-AF_{NW}, RPI-AF_{OW}, RPI-AF_{OI}, RPI-AF_{OII} and RPI-AF_{MO} are also considered in the modeling procedure and cup sizes range approximately from A to E, respectively. Figure 3 shows 3D anterior and lateral views of the RPI BMI-adjustable male and female phantoms.

For validation purposes we virtually measured several physical characteristics of the RPI BMI-adjustable male and female phantoms developed in this study and compared them with anthropometric data reported in the literature.

Ogden *et al* (2004) collected data on the body size of 196 male and female patients undergoing chest and abdominal CT examinations. The results provided trend equations for estimating a patient's anterior-posterior (AP) and lateral dimensions at mid-chest and mid-abdomen as a function of their weight. These same measurements were virtually performed on the RPI BMI-adjustable phantoms, as illustrated in figure 4. The AP and lateral measurement at mid-chest and lateral measurements at mid-abdomen of the RPI BMI-adjustable phantoms show a close fit with the Ogden *et al* trend lines (figures 5(a)–(d)). The AP dimensions at mid-abdomen for the RPI BMI-adjustable female phantoms (figure 5(c)) are slightly larger than the values predicted by Ogden *et al* trend line, but are still within the spread of Ogden *et al* data. Furthermore, the patient sample of Ogden *et al* included pediatric patients and his trend equation is sex-averaged. These results suggest that the BMI-adjustable phantoms created in this project are a realistic enough representation of overweight and obese patients for the purposes of estimating CT imaging doses.

The total adipose tissue mass was calculated for all ten BMI-adjustable phantoms and the results were compared with those calculated according to published trend equations (Deurenberg *et al* 1991, Jackson *et al* 2002). Deurenberg *et al* (1991) and Jackson *et al* (2002) used densitometry and anthropometry to develop formulas for describing the relationship between body fat percentage and BMI. Using these formulas, the predicted body fat mass was calculated for each of the RPI BMI-adjustable phantoms. These predicted values are found to be in good agreement with direct calculations as shown in figure 6. The results in figure 6 also confirm that for similar BMI values, the RPI BMI-adjustable female phantoms have more body fat than do the male phantoms, as has been reported in the literature (Camhi *et al* 2011).

In summary, all ten BMI-based phantoms created in this study were found to be consistent with the anthropometric data for overweight and obese individuals described in the literature.

3.2. Absorbed dose and effective dose to patient phantoms using BMI-adjustable phantoms

To study the effects of SAT and VAT on CT radiation dose, CT CAP scans were simulated for all ten phantoms using the same tube potential of 120 kVp and current time of 100 mAs. As CAP scans do not cover the entire body, the primary focus of this study is on CT radiation dose to organs that are fully included in the scan region (e.g., colon, lungs, stomach, liver, etc). Although not the primary focus, the radiation doses to the organs located outside the scan region (e.g., brain, thyroid, salivary glands) are also included in the final results.

Figure 7 is a plot of the organ dose results for each of the RPI BMI-adjustable phantoms normalized to those of the normal body weight phantom. As the same tube potential (120 kVp) and current time (100 mAs) were used for all ten phantoms, the CT radiation doses to superficial organs (e.g., breast) within the scan region for all the different BMI value phantoms are found to decrease slightly. However, organs deep within the body (e.g., colon, stomach, gonads, urinary bladder and liver) were highly shielded by VAT and/or SAT and the dose values for these organs decreased significantly with increasing BMI values for both phantom genders. For example, a 5%–16% and a 9%–24% reduction in breast dose was observed for the male and female phantoms, respectively, as the BMI increased from an overweight to a morbidly obese weight classification. However, for the colon, more significant reductions were observed with these values ranging from 9% to 57% in the male phantoms and 18% to 59% in the female phantoms. As the skin mass changes with increasing BMI value, the average dose to the skin was found to decrease from 7% to 13% in the male and 4% to 11% in the female. However, after accounting for the differences in the skin mass of each phantom, it was found that the total energy deposited in the skin increased with BMI by factors of 1.07–1.28 in the male and 1.02–1.19 in the female. This demonstrates that obese patients receive a higher skin exposure because the distance between the skin and CT x-ray source decreases.

Although using the same tube potential and current-time values is convenient for comparison, this is not a clinically realistic scenario. The increased photon attenuation due to the thicker body dimensions of overweight and obese patients must be compensated for by either a greater tube current and/or a higher tube potential in order to maintain an acceptable image quality. For example, for a morbidly obese patient, the tube potential of 120 kVp is often increased to 140 kVp to improve the penetration of photons through the extra thickness by the SAT and VAT (Kalra *et al* 2008). The relationship between the tube potential and patient dose is known to be nonlinear (Kalra *et al* 2008, Mahesh 2009). A higher tube potential results in an increased x-ray tube output and the higher energy photons produced can penetrate the patient's body more easily. However, the relationship between the radiation dose, image noise and kVp setting is quite complex and the proper selection of kVp depends on the desired image quality for a given examination (Mahesh 2009). For larger patients, an increase in the tube potential can also increase the organ doses received by the patient. In this study, when the tube potential was increased from 120 to 140 kVp for the obese phantoms while keeping the mAs setting constant, the organ doses for the RPI-AM_{MO} phantom increased by as much as 62% as shown in figure 8 (RPI-AF_{MO} follows the same trend, increasing by as much as 59%). This increase in the organ doses is primarily caused by the higher photon output from the x-ray source per mAs when the kVp is increased and the higher average photon energy of the x-ray spectrum. However, as illustrated in figure 8, the organ doses for organs deep in the abdominal region (e.g., colon, stomach, gonads, urinary bladder and liver) are smaller for the morbidly obese phantom compared to the normal weight phantom when a 120 kVp tube potential is used for both phantoms. These organs are heavily shielded by the extra adipose tissue, especially by the VAT (figure 3(a)). The concept of VAT offering a shielding effect was further validated by

replacing the VAT in obese individuals with normal body tissue of density 1.05 g cm^{-3} and then repeating the same CAP scans. This resulted in an increase in the dose to organs deep in the abdominal region by as much as 16% and 32% for the morbidly obese male and female phantoms, respectively, because there is less organ shielding. While the realism of our model for VAT may be further improved in the future, the results of this study already clearly suggest that VAT should be considered when calculating radiation dose for obese individuals.

Clinically, the tube current can also be increased to improve image quality for obese patients. X-ray beam attenuation is naturally greater for overweight and obese patients because of the extra thickness of adipose tissue. A rough rule of thumb is that the x-ray beam intensity and penetration halve for each additional 4 cm of body thickness (Carroll 2007). Image noise is inversely proportional to the tube current. However, for a given exposure time, the CT radiation dose is directly proportional to the tube current suggesting a clear tradeoff between image quality and radiation dose. In practice, the tube current is usually adjustable over a wide range from a few mA to several hundred mA in most CT scanners. For obese patients, an increase in mAs by a factor of 2 is often appropriate (McCollough *et al* 2009). In such a scenario, doubling the tube current-time product from 100 to 200 mAs results in a double of the organ dose ratios shown in figure 7.

To better estimate the radiation risk from the CT examination, the sex-averaged effective doses were also calculated. We derived the effective dose results from the CAP scans for each body weight classification and normalized them to the same CT x-ray tube current output in units of mSv/100mAs, as summarized in table 4. Effective dose estimates can be easily calculated by multiplying the values reported in table 4 by the applied tube current-time product. It was found that doubling the mAs for obese patients while using the same 120 kVp tube potential results in an increase in effective dose by 57%, 42% and 23% for the obese-I phantom, obese-II phantom and Morbidly-obese phantom, respectively, compared to that of the normal weight phantom.

4. Conclusions

The number of overweight and obese individuals in the United States is increasing. This study has shown that the radiation dose to a patient can be greatly affected by his or her size and stature. It would be difficult to quantify this relationship without computational phantoms representing overweight and obese patients.

This study took advantage of recent advancements in deformable computational phantoms and focused on the overweight and obese patient populations that have been neglected in the past. A total of ten phantoms with different BMI values ranging from 23.5 kg m^{-2} (normal weight) to 46.4 kg m^{-2} (morbidly obese) were developed for CT dose calculations using the MCNPX code. It was found that the radiation dose to an overweight or obese patient is affected not only by the total patient torso size but also by the total adipose tissue mass; for a constant 120 kVp tube potential and current-time product of 100 mAs, the results showed that the radiation dose to organs deep in the abdomen were reduced by as much as 57% and 59% in the obese male and female phantoms, respectively, compared to their normal weight counterparts. This effect was found less significant for shallow organs such as skin and breast. It was also found that if VATs were ignored in the modeling process of obese individuals (i.e. replaced by normal body tissues), the dose to organs deep in the abdominal region increased by as much as 16% and 32% in the obese male and female phantoms, respectively. The results from our simple VAT model suggest that VAT plays an important role in the organ dose estimates and should always be considered for obese individuals. As

expected, the data confirm that an increase in kVp and mAs results in an increased absorbed organ dose and effective dose to the obese patients.

The obese phantoms created in this study can be used in the future to study image quality and organ doses for optimization of CT, as well as PET, SPECT and interventional radiography. In addition, the CT organ doses calculated in this study for a GE scanner can be used to estimate dose from other scanners with a method suggested by Caracappa *et al* (2010) that involves deriving organ-specific adjustment factors or by using CTDI_{vol} as a normalization factor to account for the different organ doses between different scanners as suggested by Turner *et al* (2010). More scan protocols may be considered in the future to study the effect of patient size on radiation dose and image quality. Such future studies would support dose-saving efforts that are currently the focus of a number of AAPM task groups such as TG-111 (AAPM 2010) on the evaluation of radiation dose in x-ray computed tomography and TG-204 (AAPM 2011) on size-specific dose estimates in adult body CT examinations. The ultimate goal of this on-going work is to include dose data for these obese phantoms in a CT dose reporting software tool called 'VirtualDose' (Ding *et al* 2010a).

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Figure 1.

A cross-sectional image of the abdomen illustrating the division of adipose tissues into two main classes: (1) subcutaneous (SAT): off-white colored tissues located outside the dashed circle and (2) visceral (VAT): off-white colored tissues inside the dashed circle.

Figure 2.

A visualization of the adipose tissue modeling for the RPI BMI-adjustable male phantoms: (a) abdominal organs (surface rendering mode) and VAT (wireframe rendering mode) which surrounds the abdominal organs, (b) SAT layer beneath the skin, defined as the region between the body surface and internal body cavity. As the fat tissue is not defined in the ICRP's radiosensitive organ list, SAT and VAT only serve to attenuate photons.

Figure 3. Anterior and lateral views of the RPI BMI-adjustable (a) male and (b) female phantoms. The phantoms have the same height (1.76 m in the male and 1.63 m in the female) but differ in weight. From left to right the weight classifications are normal-weight, overweight, obese level-I, obese level-II and morbidly obese.

Figure 4.

Examples of cross-sectional images at (a) mid-chest and (b) mid-abdomen which are used to virtually measure the AP and lateral dimensions (images originally obtained from the data set of the National Library of Medicine's visible human project, <http://www.nlm.nih.gov/research/visible>).

Figure 5. Body dimension versus weight for the RPI male and female obese phantoms: (a) AP dimension at mid-chest, (b) lateral dimension at mid-chest, (c) AP dimension at mid-abdomen and (d) lateral dimension at mid-abdomen. Also plotted in dashed lines are fitted sex-averaged trend curves reported in the literature (Ogden *et al* 2004).

Figure 6. Comparison of fat masses in the RPI male and female obese phantoms with values based on published prediction formulas (Deurenberg *et al* 1991, Jackson *et al* 2002) using the BMI value of each phantom. Agreements between these two sets of data are observed.

Figure 7. Comparison of organ doses for RPI adult normal body weight, overweight, obese phantoms: (a) males and (b) females. The same tube potential (120 kVp) and tube current time (100 mAs) are used.

Figure 8.

Plot of the organ dose ratios of the RPI-AMMO when tube potential increases from 120 to 140 kVp without changing the mAs setting and the organ dose ratios increase significantly with the tube potential increasing, ranging from 41% to 62%.

Table 1

Clinical weight classification based on BMI (WHO 2011).

BMI (kg m ⁻²)	Weight classification
<18.5	Underweight
18.5–24.9	Normal weight
25–29.9	Overweight
30–34.9, 34.9–39.9	Obese (I, II)
>40	Morbidly obese

Table 2
The weight classifications of the RPI BMI-adjustable male and female phantoms.

Weight classification	Male (height 1.76 m)		Female (height 1.63 m)	
	Phantom	Weight (kg) BMI (kg m ⁻²)	Phantom	Weight (kg) BMI (kg m ⁻²)
Normal weight	RPI-AM _{NW}	72.7 23.5	RPI-AF _{NW}	63.5 23.9
Overweight	RPI-AM _{OW}	85.7 27.7	RPI-AF _{OW}	75.3 28.3
Obese I	RPI-AM _{OI}	103.1 33.3	RPI-AF _{OI}	90.6 34.1
Obese II	RPI-AM _{OII}	117.0 37.8	RPI-AF _{OII}	102.4 38.5
Morbidly obese	RPI-AM _{MO}	139.4 45.0	RPI-AF _{MO}	123.3 46.4

Waist circumference (WC), total subcutaneous fat (SAT) mass and total visceral fat (VAT) mass for the RPI BMI-adjustable male and female phantoms.

Table 3

Phantom	Male (height 1.76 m)			Female (height 1.63 m)		
	WC (cm)	SAT (kg)	VAT (kg)	Phantom	WC (cm)	SAT (kg)
RPI-AM _{NW}	92.6	8.1	2.9	RPI-AF _{NW}	88.1	12.9
RPI-AM _{OW}	99.1	14.2	3.6	RPI-AF _{OW}	99.4	23.0
RPI-AM _{OI}	114.3	24.4	5.3	RPI-AF _{OI}	108.4	28.9
RPI-AM _{OII}	126.8	31.4	6.5	RPI-AF _{OII}	119.7	39.2
RPI-AM _{MO}	139.5	50.9	7.9	RPI-AF _{MO}	139.6	57.7

Table 4

Effective doses (mSv/100 mAs) from CAP scans for RPI phantoms of different weight classification.

Weight classification	CT examination type: CAP	
	Tube potential (kVp)	Effective dose ^a (mSv/100mAs)
Normal weight	120	6.69
	140	9.95
Overweight	120	6.04
	140	9.05
Obese-I	120	5.26
	140	7.92
Obese-II	120	4.76
	140	7.04
Morbidly obese	120	4.12
	140	6.27

^aICRP Publication 103 defines effective dose as a sex-averaged value (ICRP 2007).