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“Increased Radiation Dose to Overweight and Obese Patients from Radiographic Examinations”

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Abstract

**Purpose:** To estimate the increase in effective dose from diagnostic x-rays for overweight and obese adult patients compared with ‘lean’ reference phantoms.

**Materials and Methods:** Relative effective doses, \(E/E_0\), for chest and abdomen radiographs were calculated using Monte Carlo simulation of Oak Ridge National Laboratory adult phantoms with \((E)\), and without \((E_0)\), subcutaneous adipose tissue added to the phantom torso for five distinct fat distributions. Total anterior plus posterior fat thicknesses ranged from 0 to 38 cm.

**Results:** For 30 cm of additional fat \(E/E_0\) values for 120 kVp chest and 80 kVp abdomen radiographs ranged from approximately 2 to 31 and 83 for males, respectively, and 2 to 45 and 76 for females, depending upon the type of fat distribution and patient orientation in the x-ray beam (AP or PA). \(E/E_0\) was minimized by orienting the patient with the thinnest fat layer facing away from the x-ray tube, and was well approximated by \(E/E_0 = [B(t)/B_0]\exp(kt_{DF})\) where \(B(t)\) and \(B_0\) are the antiscatter grid Bucky factors for patient thicknesses of \(t\) and \(t=20\) cm, respectively, \(k\) a constant, and \(t_{DF}\) the distal (beam exit) fat layer thickness. Reductions in \(E/E_0\) reached 14\% and 20\% for the thickest phantoms when x-ray tube kilovoltages were increased by 10 and 20 kV, respectively, for an abdominal exam in the male.

**Conclusions:** Effective doses from radiographic examinations in the extremely obese can exceed 100 mSv from only a small number of abdominal exams and should be minimized to the extent possible and monitored. Exponential dose increases from increased subcutaneous fat thicknesses can be significantly reduced by positioning the patient so that the thinnest fat layer (anterior or posterior) is closest to the image receptor. Increasing the kVp will also reduce dose, but to a much lesser extent.
I. Introduction

Doses from diagnostic x-rays contribute the largest component to irradiation of the general public\(^1\). However, radiation dose estimates from diagnostic radiology are based on a representative ‘normal weight’ Reference Man that no longer conforms to the present US population. In this paper we investigate the increase in radiation dose to overweight and obese patients from diagnostic radiographic examinations.

Much of the published radiological data have been based on phantoms whose dimensions were designed to be typical of the North American and European populations in the mid to late 20\(^{th}\) century, as described by reports 23 and 89 of the ICRP\(^2,3\). Examples of phantoms based on these dimensions come from the Oak Ridge National Laboratory (ORNL) series which includes models of both genders and ages varying from newborn to adult\(^4\). These phantoms have been used extensively in the calculation of patient dose in diagnostic radiology.

Over the past 50 years the prevalence of both overweight and obesity has substantially increased in the United States to the extent that commonly used reference phantoms are no longer representative of average American adults. According to recent epidemiological data published by the Centers for Disease Control, 67 \% of men and 62 \% of adult women are overweight. Thirty-four percent of women and 28 \% of men can be further classified as obese\(^5\). Huh and Bolch have investigated the extent to which the ORNL phantoms (and others) represent the average US population of today\(^6\). They find that while the adult male phantom is a good match to the 21-year old male of today, present-day 40-year olds have a body mass approximately 16\% higher, with the discrepancy increasing through age 70. The discrepancy is much larger for adult females who, in the US, are on average 16-18 kg heavier than reference woman (ICRP 89) and the ORNL adult-female phantom\(^6\).

In this paper we estimate the increase in effective dose from diagnostic x-rays for overweight and obese adult patients compared with ‘lean’ reference phantoms. This dose increase is determined using computer simulated doses to the lean reference phantoms with (E), and without (E\(_0\)), added fat.

II. Materials and Methods:
A. Monte Carlo Software and ICRP Reference Man Dose Calculations
Calculations were performed using software† that assembles input files modeling various anthropomorphic phantoms and x-ray beams in the required format for simulation with MCNPX (Monte Carlo N-Particle⁷), a state-of-the-art radiation transport code developed and maintained by the Los Alamos National Laboratory. Detector and phantom descriptions are pre-stored. Exam-specific details such as patient gender and size, additional fat tissue, beam size, position on the body, and energy spectrum are selected via a user-interface and entered into the input file which is then used in an MCNPX simulation. The absorbed radiation dose in each organ and in body muscle tissue is tallied. At the completion of the simulation, the effective dose, \( E \), is calculated as the weighted sum of the individual organ doses using the tissue weighting factors published in ICRP 60⁸. Calculations of \( E \) based on tissue weighting factors recommended by ICRP 103⁹ were also performed for some cases and results compared with those based on ICRP 60.

The phantoms used in this investigation are shown in Figure 1(a) and have been patterned after the adult male and female anthropomorphic phantoms described by Cristy and Eckerman⁴. The adult male phantom was designed to closely approximate the height, weight, and internal organ descriptions of Reference Man provided in ICRP 23² and is 178.8 cm in height and weighs 76.25 kg. The adult female weighs 58.1 kg and is 168 cm tall. Tissue densities and elemental composition are from ref. 3. To examine the effect of subcutaneous fat on dose to each phantom, varying thicknesses of adipose tissue were added to the anterior, lateral, and posterior regions of the torso as shown in Figure 1(b). This fat tissue is positioned under the skin and extends in the same proportions from the bottom of the pelvis to the top of the shoulders. The fat layer does not cover the breasts in the female model until the fat thickness is greater than the extension of the breasts from the torso. The effects of interstitial fat are not addressed.

Five different fat distributions (body types) were investigated (see Figure 1(b)). Each body type is represented by a different ratio which varies the relative amounts of adipose tissue added to the anterior, lateral, and posterior regions of the reference phantoms. For a given ratio, ten simulations were performed with each one systematically increasing the fat thicknesses while maintaining the same anterior/lateral/posterior fat ratio. Figure 1b also shows axial illustrations of the five different fat distributions (shown at the largest thicknesses modeled) as applied to the

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† www.edose.us
reference male phantom. Figure 1(c) shows the relationship between total patient thickness and both anterior and posterior fat thicknesses for each body type.

In each Monte Carlo simulation a 12 cm diameter air-filled detector (tally) region was positioned 5 cm behind the patient and the exit dose, or air kerma K, to this region was measured using x-rays entering the detector from any forward direction. Normalized effective doses without (E_0/K) and with (E/K) additional fat thicknesses were calculated, and E/E_0 was determined by dividing E/K by E_0/K. This dose normalization is equivalent to maintaining a constant patient exit dose at the image receptor for both E and E_0, thereby simulating a radiographic automatic exposure control system. This is required to achieve a consistent optical density for screen-film systems or a consistent noise level for digital radiography systems, independent of patient size or tissue density.

B. Radiographic Projections

The effect of additional fat on effective dose was separately examined in the abdomen and the chest. Both AP (anterior-posterior), and PA (posterior-anterior) patient orientations were investigated. Chest exams were performed using the 120 kVp photon beam with 3 mm Al total filtration (HVL = 4.69 mm Al) described by Birch et al^{10}. The x-ray tube focal spot was simulated as a point source 182 cm above the image receptor with a rectangular x-ray field size of 35 x 43 cm at the image receptor plane. Abdominal scans were performed using an 80 kVp beam filtered with 3 mm Al total filtration (HVL = 3.03 mm Al)^{10} with a source to image distance of 102 cm.

C. Model Validation

Accuracy of the phantom models and validation of the set-up for radiographic simulation were investigated by comparing organ dose estimates for chest and abdominal exams in the male with data published by the National Radiological Protection Board (NRPB) for similar exams using the same source spectra^{11}. Effective dose comparisons using only those organs included in the NRPB dataset were also made. The phantoms used are substantially similar although small differences exist. The NRPB model is a hermaphrodite, 4.8 cm shorter than the model used here. It does not include an esophagus and the thyroid is positioned deeper within the neck. Tissue compositions and densities were changed from those given in ref. 3 to those used in the NRPB study. Attempts were made to closely match the position of the beam on the phantom as illustrated schematically in the NRPB publication. However additional simulations were performed in which
the beam was shifted up or down the longitudinal axis of the body by 2.5 cm to examine the potential effect of beam mis-positioning.

For organs fully in the radiation field, agreement with the NRPB organ dose data was within 10%. For many organs only partially in the field similar levels of agreement were reached with small (+/- 2.5 cm) adjustments in longitudinal beam position. Agreement in E was within 6% for abdominal exams and 10% for chest exams but in all cases agreement was again improved upon minor repositioning of the beam. This level of agreement is considered reasonable given the small differences in phantom geometry and, more importantly, the differences in photon interaction physics and interaction cross sections between MCNPX and the in-house NRPB Monte Carlo codes.

D. Increasing X-Ray Beam Energy

Increasing x-ray beam energies to ensure that the required number of photons reaches the image receptor while maintaining reasonably short exposure times is common practice when imaging larger patients. To examine the effects of increasing beam energy, E/E₀ values were recalculated for the 80 kVp AP abdominal projection at 90 kVp (with 3 mm aluminum total filtration; HVL = 3.43 mm Al) and 100 kVp (with 4 mm aluminum total filtration; HVL = 4.46 mm Al)¹⁰. Chest exams were repeated at 140 kVp (with 3 mm aluminum total filtration; HVL = 5.5 mm Al)¹⁰.

E. Antiscatter Grids

Antiscatter grids increase patient dose by blocking scattered photons from entering the image receptor, requiring a greater number x-rays incident upon the patient. Thicker patients generate more scatter and hence the incident x-ray intensity must be further increased. The dose increase from using an antiscatter grid was incorporated by multiplying the E/E₀ ratios, calculated without the presence of a grid, by B(t)/B₀, where B(t) and B₀ are the Bucky factors for patients with total AP thicknesses t and t = 20 cm, respectively. The Bucky factors were derived from grid transmission and scatter to primary ratio data measured by Fetterly et al¹² under planar radiography conditions. For a typical 12:1 ratio 80 lines per inch grid, B(t) increased from 4.5 for a 20 cm thick lean patient to 6.4 for one with 30 cm of additional fat (50 cm total patient thickness). B(t)/B₀ ranged from 1 to 1.42. Although Fetterly et al’s measurements were acquired using planar slabs of Solid Water®, the slab thicknesses were not renormalized to lean or fat tissue equivalents for two reasons: Only ratios of Bucky factor are used, which cancel out most of these corrections,
and the variation of \( B(t)/B_0 \) as a function of patient size is very small compared with the \( E/E_0 \) ratio increases without the grid.

**F. Data Analyses**

Chest and abdominal examinations were performed for each phantom (male or female), beam orientation (AP or PA), beam energy (80, 90 or 100 kVp in the abdomen and 120 or 140 kVp in the chest), and fat distribution (body types 1 through 5), for a total of 100 different conditions. Ten simulations were performed for each condition. The ten simulations varied the fat thicknesses while maintaining the same anterior/lateral/posterior fat ratio. More than one thousand simulations were performed. Typical statistical uncertainties associated with in-field organs and exit doses were 0.01 – 1 % leading to dose-weighted uncertainties in \( E \) of approximately 1 % except for some cases associated with the thickest phantoms for which the error in \( E \) reached 3-4 %. Estimated values of \( E \) for overweight phantoms were normalized by exit dose and then divided by \( E_0/K \), the normalized effective dose to the lean model for the same exam conditions. Values of \( E/E_0 \) were then plotted as a function of either anterior, posterior, or total fat thickness. Resultant curves were fit to a single exponential of the form \( y = \exp(kt) \) using Microsoft Excel© software and the method of least squares. \( y (= E/E_0) \) was forced to equal a value of 1.0 at zero additional fat thickness \( (t=0) \). Best fit values of \( k \) and the corresponding coefficients of determination, \( R^2 \) where \( R \) is the correlation coefficient, were tabulated for each condition. The coefficient of determination was greater than 0.98 in all but 14 of the 100 conditions but in no case was below 0.91. The mean of the absolute percent differences between each exponential curve and the calculated \( E/E_0 \) values was also calculated. The average of these means over all body types, kVp’s, and orientations were 3.9% (2.0%) and 4.4% (2.1%) for males and females, respectively. The quantities in parentheses are the standard deviations.

**III. Results**

The relative increase in effective dose caused by excess body fat is illustrated in Figure 2 which plots \( E/E_0 \) for abdominal exams in the adult male, prior to accounting for the antiscatter grid. In each figure the individual curves show the calculated effective dose scaling factors, \( E/E_0 \), for the five different body types investigated. Figures 2a - 2c show the results of AP projections and plot scaling factors as a function of (a) anterior fat thickness, (b) posterior fat thickness and (c) total
patient thickness (including the 20 cm thick ‘lean core’ of the reference male phantom plus the additional anterior and posterior fat). Interestingly, the dose ratios are essentially identical for each body type only when plotted against the thickness of fat on the distal (beam exit) side of the body (Figure 2b). A similar result was observed with the PA abdominal projection as shown in Figure 2d which plots E/E₀ versus anterior fat thickness for the PA orientation in the male. This finding was consistently seen for all exams investigated, for both orientations, and in both phantoms. That is, for each exam and orientation the thickness of fat on the beam exit side of the body is a reliable predictor of the dose increase due to the effects of photon attenuation through fat.

Dose increase as a function of distal fat thickness for all exams, prior to accounting for the antiscatter grid, is plotted in Figure 3 for projections of the (a) male chest, (b) male abdomen, (c) female chest, and (d) female abdomen. The data points in Figure 3 include E/E₀ ratios for all the five body types investigated. The resultant curves can be expressed as single exponentials of the form \( \exp(kt_{DF}) \), where \( k \) is given in Table 1 for each projection, and \( t_{DF} \) represents the thickness of distal fat. This fat thickness can be estimated using Figure 1(c) after measuring the total patient thickness, and visually estimating the patient’s body type.

Analyses were performed using the tissue weighting factors included in ICRP 60⁸. Many of the cases were then re-analyzed using tissue-weighting factors suggested in ICRP 103⁹ and the impact on E/E₀ evaluated. Only in the female AP Chest exam did the ratio of E/E₀ change significantly when using the newer weights, a consequence of the substantial increase in the weighting factor assigned to breast tissue from 0.05 in ICRP 60 to 0.12 in ICRP 103⁹. For the AP chest exam, the change in the fractional contribution of breast dose to total effective dose results in an increase in the E/E₀ ratio that reaches 16 % for the largest females (body types 1 and 2).

The effects of increasing x-ray beam energy are shown in Figure 4 which plots E/E₀ for the AP abdomen projection in the adult male as a function of total fat thickness. The dose reduction is greatest for the largest patients but reaches only 14% with an increase of 10 kVp and 20% when the beam energy is increased from 80 kVp to 100 kVp for a 44 cm thick patient with 24 cm of additional fat (body type 4). These findings are approximately consistent with those of Gkanatsios et al¹³ who investigated the reduction in effective dose to a 20 cm thick (water equivalent) phantom as a function of kVp in digital subtraction angiography. The dose reductions realized in
using higher energy beams are modest compared with much greater $E/E_0$ increases when significant subcutaneous fat is present.

The data displayed in Figures 2-4 reflect the effects of increasing photon attenuation in thicker patients without the presence of the antiscatter grid. Figure 5 plots the relative increase in dose, $B(t)/B_0$, due to the grid alone, as a function of total phantom thickness. The curve shown in Figure 5 can be represented by the expression: $B(t)/B_0 = (0.37295)\ln(t-5.3426)$ where $t$ is the total AP (or PA) patient thickness. Relative to the magnitude of $E/E_0$, the increase in the Bucky factor with phantom thickness ($B(t)/B_0$) is a slowly varying function of total patient thickness. Thus, when the values of $E/E_0$, shown in Figure 3, are multiplied by the Bucky factor, the result can again be approximated by a single exponential of the form $\exp(k't_{DF})$, where values of $k'$ and the associated $R^2$ coefficients are given in Table 1.

The increased dose to overweight individuals is the result of both photon attenuation through larger thicknesses of tissue (shown in Figure 3) and rejection of a larger fraction of photons reaching the image plane due to scatter within the phantom (Figure 5). The product of both effects is presented in Figure 6 for exams of the (a) male chest, (b) male abdomen, (c) female chest, and (d) female abdomen. Curves in Figure 6 are plotted as a function of total fat thickness. Each plot in Figure 6 consists of two sets of curves, one set for each projection (AP or PA) and one curve for each body type.

As shown in Figure 6, $E/E_0$ grows exponentially as the thickness of excess fat increases. For an extremely overweight male with 25 cm additional fat around the abdomen, the effective dose delivered from an abdominal exam can be greater than 40 times larger than the dose an adult male of Reference Man proportions would receive from this same procedure. For 30 cm of additional fat (not shown in figure) it can be 83 times greater. Similar increases are seen in the adult female. The magnitude of the dose increase is affected not just by total patient thickness but by fat distribution (body type) and patient orientation with respect to the x-ray source. Figure 2 demonstrates that it is the thickness of the fat layer closest to the image receptor that plays the dominant role in determining effective dose increase.

The magnitude of the patient orientation effect (PA or AP) is compared in Table 2 which shows values of $E/E_0$ for three overweight male patients. Each patient has a markedly different distribution of fat although the total added thickness in the anterior plus posterior direction is
approximately the same (18 cm). Both AP and PA orientations are compared for abdomen and chest exams. Clearly, for a patient exhibiting more anterior fat than posterior fat, an AP orientation leads to a lower effective dose, by a factor of approximately 4-5 for an abdominal exam and 2-3 for a chest exam. Thus, effective dose scaling factors are substantially lower when the patient is oriented such that the thickest region of fat is placed toward the x-ray tube. For a more extreme case, a male patient with body type 1 and 25 cm of total additional fat, \( \frac{E}{E_0} \) changes from approximately 3 for an AP abdominal exam to over 40 with a PA orientation (Figure 6(b)).

Figures 1 and 6 can be conveniently used to estimate \( \frac{E}{E_0} \) ratios for specific patients. For example, consider a chest exam on a 55 cm thick adult female with an estimated body type 3. From Fig. 6c, for AP and PA chest exams in an adult female, the effective doses, with respect to a 20 cm thick lean female, are 6 and 28 times greater, respectively. This result could also be calculated using the equation \( \exp(k't_{DF}) \) with the \( k' \) values from Table 1 and an estimate of distal fat thickness. From Figure 1(c), a 55 cm thick patient with an estimated body type 3, has approximately 23.5 cm of anterior fat and 12 cm of posterior fat. Thus, for the AP and PA chest exams \( \frac{E}{E_0} = \exp(0.1482*12) = 5.9 \) and \( \exp(0.1423*23.5) = 28 \), respectively. Note, however, that the effective dose scaling factors plotted in Figure 6 were determined using the Bucky factors shown in Figure 5. These, in turn, were based on measurements described by Fetterley et al who used a 12:1 ratio 80 lines per inch grid\(^{12}\). Use of a different antiscatter grid will lead to somewhat different predictions of the increase in effective dose for a given patient. However, for the grid ratios and line rates commonly used in adult radiography for body exams, differences in the \( \frac{B(t)}{B_0} \) ratios compared with the values used here should be small. If \( \frac{B(t)}{B_0} \) for a different grid is known, \( \frac{E}{E_0} \) can also be calculated by multiplying \( \frac{B(t)}{B_0} \) by \( \exp(k_{DF}) \), where \( k \) is the exponential coefficient from Table 1 without a grid.

The effective doses to a lean adult male (Reference Man) from various standard imaging procedures, as reported in the literature\(^{14,15}\), are given in Table 3. Also given are the values of effective dose from the same procedure performed on either moderately (15 cm total added thickness in the region being imaged) or very (25 cm additional fat thickness) overweight patients. Doses to overweight patients (obtained from Figure 6) are given assuming a patient with body type 3 (with the full range of potential dose increase resulting from the five different body types provided in parentheses).
All doses listed in Table 3 are provided in units of milliSieverts (mSv) and Background Equivalent Radiation Time (BERT)\(^6\). The BERT expresses the effective dose in terms of the time required to receive the same effective dose from natural background radiation and, while not an official unit of radiation dose, is useful in providing context and a frame of reference in discussions with patients. Average natural background radiation levels in the United States are approximately 2.8 mSv/year\(^1\).

Based on assumptions of a lean patient, a typical AP abdominal examination has been reported\(^{14}\) to deliver an effective dose of approximately 0.70 mSv, as shown in Column 2 of Table 3. This dose is the same as the dose one already receives simply from living approximately 90 days with average natural background radiation levels in the US. However, if a moderately overweight man (15 cm of additional thickness) undergoes this same abdominal examination, his effective dose will be a factor of 2-10 times greater (depending on his fat distribution). His effective dose will be 1.4-7.0 mSv. For a patient with 25 cm additional fat in the abdominal region, the E/E\(_0\) scaling factors range from 3- 40, leading to effective doses from this exam of 2.1 to 28 mSv. At 28 mSv, only four abdominal radiographs would exceed 100 mSv, which, using the linear no threshold radiation risk model, carries a risk of a radiation induced cancer of approximately 1 out of 170 or 0.6\(^\%\)\(^8,9\). This falls within the range of moderate risk, as compared with minimal or extremely low risk for a single abdominal radiograph for an average size patient\(^{17,18}\).

**IV. Discussion**

The importance of the fat layer closest to the image receptor in determining E/E\(_0\) is due to the definition of effective dose and the different roles proximal and distal fat play as radiation attenuators. Effective dose includes only organs or tissues with significant susceptibility to radiation-induced cancer\(^8\). Radiation-induced cancers in fat have not been demonstrated to be of significance\(^19\). The fat on the beam exit side of the body (‘distal’ fat) intercepts the x-ray beam after it has interacted with the ‘lean core’ containing the radiosensitive organs. This distal fat increases the dose to the core organs exponentially since it acts simply as an additional attenuator between the core and the image receptor, forcing the x-ray system to increase its output to maintain a constant target exit dose. The fat on the proximal side also requires increased x-ray
output, but this just increases the patient skin and proximal fat doses without increasing the core
dose.

The results presented here are in the form of a relative comparison of the same phantom
with and without additional fat tissue. Therefore, any anatomical limitations in the original
phantom are approximately cancelled out, leaving only the effects of the additional fat. Similarly,
the results are expected to be largely independent of the choice of lean phantom used in the
calculations. That is, the differences in phantom thickness and organ placement amongst lean
models (eg. reference man as specified in ICRU 23\textsuperscript{2}, reference man as specified in ICRP 89\textsuperscript{3}, and
the ORNL adult phantom\textsuperscript{4}) are small and are unlikely to affect the relative increase in \(E\) calculated
by comparing dose to the lean phantom with and without added fat. It is the modeling of adipose
tissue that introduces the greatest anatomical limitation. Adipose is added as an elliptical cylinder
throughout the entire length of the torso. This is an oversimplification of the ‘apples’ or ‘pears’
distributions more typically observed in adult body types\textsuperscript{20}. However, the relevant feature of the
subcutaneous fat in this study is the thickness of fat over- and under-lying the anatomical region
being imaged. The presence or absence of fat proximal to the x-ray tube has only a very minor
impact on the results. Similarly, if the distribution of subcutaneous fat changes when the patient
assumes a supine position, it is only the thickness of fat remaining within the x-ray field (and
especially the beam exit regions of the body) that influences the patient’s effective dose. Thus, for
some patients, the supine position typical of an abdominal exam may lead to a lower effective dose
than would be expected based on the patient’s fat distribution when upright, since some of the
adipose tissue may shift to lateral positions. Lateral fat has little or no impact on effective doses
from AP or PA planar or fluoroscopic exams.

Current estimates of our yearly radiation dose, made by the National Council on
Radiological Protection (NCRP), indicate that over 50 % of our annual dose results from medical
procedures. This estimate is substantially higher than the 11% estimate made by the NCRP in
1989\textsuperscript{21}, an increase due in part to the increasing use of dose-intensive CT and to the increasing
reliance on the use of x-rays in general for the diagnosis and treatment of disease. It is important
to note that much of the data contributing to these per capita estimates are based on assuming a
lean population with height and weight characteristics represented by Reference Man. Given the
prevalence of overweight and obesity in the population it is quite likely that the per capita yearly
radiation dose is substantially higher. The increased dose per procedure for the overweight is exacerbated by the fact that the overweight and obese experience a greater number of health problems and make use of a greater number of medical services, including radiological exams\textsuperscript{22}.

To limit the increased dose to patients caused by excess body fat it is recommended that the impact of patient orientation (AP or PA) be carefully taken into consideration. Increasing the kVp also reduces patient dose, but the reduction is significantly less than patient orientation considerations and results in reduced image contrast. It is further recommended that monitoring and recording of patient dose for this population be performed for each examination. Such a pool of data might serve not only as a tool for improved patient management from a radiation safety standpoint, but also as a potential source of data for future epidemiological studies on the effects of low dose radiation in humans. Given the dominance of medical radiation in our annual radiation dose, the frequency of radiological examinations, and the fact that radiology patients is the only population we routinely and deliberately irradiate, it might eventually be possible to correlate cancer risk with organ dose (or imaging procedure) stratified for a number of disease or other categories of health status (such as BMI).
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Figure and Table Captions

Figure 1. (a) 3D volume rendering of lean male (76.25 kg; 178.8 cm tall) and female (58 kg 168 cm tall) reference models patterned after the ORNL adult phantoms. Adipose tissue was added in five different configurations corresponding to five “body types”. These are expressed in (b) as ratios of anterior/lateral/posterior fat added to the torso of the reference phantoms. For each ratio (body type), 10 different representations were modeled. Also shown are axial illustrations of each body type applied to the male reference phantom and displayed at the largest fat thicknesses modeled. (c) Distal subcutaneous fat layer thicknesses (anterior or posterior) as a function of total patient thickness for the five body types described in (b). Total patient thickness includes the 20 cm thick ‘lean core’ of the phantoms.

Figure 2. Relative effective doses, E/E₀, at a constant exit dose without an anti-scatter grid, for AP radiographic projections of the male abdomen as a function of (a) anterior fat thickness, (b) posterior fat thickness, and (c) total fat thickness. In (d), E/E₀ is shown for a PA abdominal radiograph in the adult male phantom as a function of anterior fat thickness.

Figure 3. Relative effective doses, E/E₀, at a constant exit dose without an anti-scatter grid, for AP and PA radiographic projections of the (a) male chest, (b) male abdomen, (c) female chest and (d) female abdomen as a function of distal fat thickness, t_{DF}, for all body types. Curves are single exponential fits to the data, exp(kt_{DF}), where k is given in Table 1 for each projection. Error bars are ± 4%. Distal fat thicknesses can be obtained from Fig. 1(c) for the different body types.

Figure 4. (a) The effect of increasing x-ray beam energy on relative effective dose, E/E₀, for an AP abdominal radiograph of an adult male with body types 1, 3, or 4 at 80 kVp, 90 kVp and 100 kVp as a function of total patient thickness. [Effects of the anti-scatter grid are not included.] (b) The effect of increasing beam energy to 120 or 140 kVp for PA chest exams in the male and female with body type 1. Data for all other exams are provided as k values in Table 1.

Figure 5. Relative Bucky factors, B(t)/B₀, as a function of total phantom (patient) thickness, t, derived using grid x-ray transmission data from Fetterly et al for a 12:1 ratio 40 cm⁻¹ line rate anti-scatter grid at 104 kVp¹². B₀ is the Bucky factor for t = 20 cm. The coefficient of determination, R², for this curve is 0.9998.

Figure 6. Relative effective doses, E/E₀, incorporating effects of the antiscatter grid as a function of total patient thickness for AP and PA radiographic projections of the (a) male chest, (b) male abdomen, (c) female chest and (d) female abdomen. Data combine the effects of photon attenuation through additional fat thickness, as shown in Figure 3, with the effects of the antiscatter grid, as shown in Figure 5. Data points are connected by straight lines, however exponential fit parameters for each curve can be found in Table 1.
Table 1. Values of the least-squares fitting parameter $k$, from $y = \exp(kt_{DF})$ fits to the $E/E_0$ data without an anti-scatter grid shown in Figure 3, and $k'$, from $y = \exp(k't_{DF})$ fits to the $E/E_0$ data with a 12:1 ratio 80 lines per inch antiscatter grid shown in Figure 6. Numbered column headings refer to the body types 1 – 5 in Figure 1(b). Numbers in parentheses are the corresponding $R^2$ values.

Table 2. A comparison of the effect of patient orientation on effective dose scaling factors ($E/E_0$). AP and PA exams in the male are compared for three patients with similar total thickness but different fat distributions.

Table 3. Effective doses resulting from various imaging procedures performed on a lean adult (Column 2), a moderately overweight patient with 15 cm additional body fat in the region being irradiated (Column 3), and a very overweight individual with 25 cm additional total fat (Column 4). Data for column 2 are from Wall and Hart 1997\textsuperscript{14} or UNSCEAR 2000\textsuperscript{15} and those for Columns 3 and 4 were obtained by multiplying values in Column 2 by the $E/E_0$ scaling factors shown in Figure 6 for a patient with body type 3. Also included in Columns 3 and 4 is the range of dose increase resulting from all body types; this is provided in parentheses. [\textsuperscript{4}In Coronary Angiography numerous views of the heart are obtained from a variety of angles around the patient. While only AP and PA views were investigated here, approximately similar values of $E/E_0$ for similar thicknesses of excess fat tissue are expected, regardless of the views employed.]
Figure 1.

(b) Body Type

| Body Type | 1 | 2 | 3 | 4 | 5 |
|-----------|---|---|---|---|---|
| Axial view of Fat Distribution | | | | | |
| Ratio of Added Fat Thickness (Anterior/Lateral/Posterior) | 6/3/1 | 1/3/6 | 4/3/2 | 2/3/4 | 1/1/1 |

Figure 1.
Figure 2(a)

(a) Male AP Abdomen

Anterior Fat Thickness (cm)

Body Type 1
Body Type 2
Body Type 3
Body Type 4
Body Type 5
Figure 2(b)
Figure 2(c)
Figure 2(d)
Figure 3(a)
Figure 3(b)
Figure 3(c)

(c) Female Chest

- PA Chest Data
- AP Chest Data
- PA Chest Exp. Fit
- AP Chest Exp. Fit

Distal Fat Thickness (cm)

E/E₀

0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80

0 5 10 15 20 25 30 35
Figure 3(d)
Figure 4(a)

Male AP Abdomen

- 80 kVp Body Type 1
- 90 kVp Body Type 1
- 100 kVp Body Type 1
- 80 kVp Body Type 3
- 90 kVp Body Type 3
- 100 kVp Body Type 3
- 80 kVp Body Type 4
- 90 kVp Body Type 4
- 100 kVp Body Type 4
PA Chest - Body Type 1

$E/E_0$

Total Patient Thickness (cm)

120 kVp Female
140 kVp Female
120 kVp Male
140 kVp Male

Figure 4(b)
Figure 5

\[ \frac{B(t)}{B_0} = a \ln(t + b) \]

\( a = 0.37295 \)
\( b = -5.3426 \)
\( R^2 = 0.9998 \)
Figure 6(a)
Figure 6(b)
Figure 6(c)
Figure 6(d)
Table 1. Values of Exponential Fit Parameters for data with and without Antiscatter Grid

| Projection | kVp |            |            |            |            |            |            |            |            |
|------------|-----|------------|------------|------------|------------|------------|------------|------------|------------|
|            |     | k cm⁻¹ (R²) | k' cm⁻¹ with grid (R²) |     |     |     |     |     |     |
|            |     | without grid |                      |     |     |     |     |     |     |
| Male       |     |            |            |            |            |            |            |            |            |
| PA Chest   | 120 | 0.1217 (0.9940) | 0.1339 (0.9966) | 0.2420 (0.9825) | 0.1387 (0.9992) | 0.1672 (0.9948) | 0.1478 (0.9990) |     |     |
|            | 140 | 0.1123 (0.9929) | 0.1273 (0.9988) | 0.2245 (0.9907) | 0.1312 (0.9988) | 0.1542 (0.9953) | 0.1390 (0.9981) |     |     |
| AP Chest   | 120 | 0.1214 (0.9933) | 0.2370 (0.9623) | 0.1337 (0.9993) | 0.1694 (0.9949) | 0.1393 (0.9995) | 0.1498 (0.9983) |     |     |
|            | 140 | 0.1139 (0.9935) | 0.2188 (0.9783) | 0.1270 (0.9993) | 0.1602 (0.9979) | 0.1317 (0.9912) | 0.1410 (0.9988) |     |     |
| AP Abd     | 80  | 0.1400 (0.9747) | 0.3261 (0.9901) | 0.1506 (0.9985) | 0.2052 (0.9937) | 0.1593 (0.9989) | 0.1723 (0.9994) |     |     |
|            | 90  | 0.1291 (0.9712) | 0.3095 (0.9966) | 0.1407 (0.9968) | 0.1895 (0.9928) | 0.1485 (0.9945) | 0.1618 (0.9960) |     |     |
|            | 100 | 0.1259 (0.9739) | 0.2923 (0.9933) | 0.1385 (0.9919) | 0.1779 (0.9975) | 0.1385 (0.9919) | 0.1551 (0.9972) |     |     |
| PA Abd     | 80  | 0.1568 (0.9891) | 0.1745 (0.9997) | 0.2751 (0.9081) | 0.1775 (0.9986) | 0.2136 (0.9782) | 0.1882 (0.9881) |     |     |
|            | 90  | 0.1490 (0.9891) | 0.1649 (0.9961) | 0.2979 (0.9779) | 0.1670 (0.9966) | 0.2035 (0.9954) | 0.1770 (0.9990) |     |     |
|            | 100 | 0.1525 (0.9850) | 0.1637 (0.9988) | 0.3050 (0.9252) | 0.1724 (0.9951) | 0.2178 (0.9903) | 0.1850 (0.9935) |     |     |
| Female     |     |            |            |            |            |            |            |            |            |
| PA Chest   | 120 | 0.1392 (0.9954) | 0.1514 (0.9992) | 0.2629 (0.9707) | 0.1597 (0.9983) | 0.1870 (0.9895) | 0.1647 (0.9938) |     |     |
|            | 140 | 0.1312 (0.9960) | 0.1446 (0.9992) | 0.2476 (0.9887) | 0.1505 (0.9985) | 0.1775 (0.9948) | 0.1557 (0.9960) |     |     |
| AP Chest   | 120 | 0.1462 (0.9865) | 0.2908 (0.9081) | 0.1559 (0.9998) | 0.2045 (0.9847) | 0.1642 (0.9895) | 0.1758 (0.9957) |     |     |
|            | 140 | 0.1421 (0.9826) | 0.2959 (0.9430) | 0.1510 (0.9987) | 0.2024 (0.9897) | 0.1617 (0.9988) | 0.1735 (0.9947) |     |     |
| AP Abd     | 80  | 0.1339 (0.9947) | 0.2464 (0.9643) | 0.1568 (0.9898) | 0.1715 (0.9889) | 0.1625 (0.9991) | 0.1673 (0.9979) |     |     |
|            | 90  | 0.1306 (0.9894) | 0.2212 (0.9846) | 0.1495 (0.9971) | 0.1609 (0.9982) | 0.1526 (0.9960) | 0.1563 (0.9935) |     |     |
|            | 100 | 0.1279 (0.9919) | 0.2193 (0.9900) | 0.1453 (0.9968) | 0.1676 (0.9974) | 0.1498 (0.9968) | 0.1529 (0.9977) |     |     |
| PA Abd     | 80  | 0.1558 (0.9955) | 0.1717 (0.9995) | 0.2890 (0.9120) | 0.1755 (0.9980) | 0.1965 (0.9865) | 0.1850 (0.9943) |     |     |
|            | 90  | 0.1488 (0.9969) | 0.1662 (0.9989) | 0.2643 (0.9509) | 0.1678 (0.9996) | 0.1915 (0.9867) | 0.1774 (0.9983) |     |     |
|            | 100 | 0.1527 (0.9894) | 0.1665 (0.9992) | 0.3067 (0.9112) | 0.1705 (0.9973) | 0.2124 (0.9917) | 0.1810 (0.9943) |     |     |
Table 2. Effect of Patient Orientation on E/E₀

| Exam and Orientation | Patient 1: Ratio 1 | Patient 2: Ratio 2 | Patient 3: Ratio 5 |
|----------------------|-------------------|-------------------|-------------------|
|                      | Total AP Fat: 17.5 cm | Total AP Fat: 17.5 cm | Total AP Fat: 18.0 cm |
|                      | Ant/lat/post.=15/7.5/2.5 | Ant/lat/post.=2.5/7.5/15.0 | Ant/lat/post.=9/9/9 |
| Abdomen AP           | 2.5               | 10.0              | 6.6               |
| Abdomen PA           | 13                | 2.4               | 5.1               |
| Chest AP             | 2.0               | 7.6               | 3.6               |
| Chest PA             | 7.1               | 2.0               | 3.6               |
### Table 3. Effective Dose to Lean, Overweight and Very Overweight Patients from Radiographic Exams

| X-ray examination       | Effective Dose |
|-------------------------|----------------|
|                         | mSv            |
|                         | BERT           |
| **Reference man**       | **Effective Dose** | **BERT** |
|                         | (mSv)          | (mSv)    |
| **AP Abdomen**          | 0.70           | 1.9      |
|                         | (1.4-7.0)      | (1.4-7.0) |
| **PA Chest**            | 0.02           | 0.08     |
|                         | (0.04-.11)     | (0.04-.35) |
| **AP Lumbar Spine**     | 0.70           | 1.9      |
|                         | (1.4-7.0)      | (1.4-7.0) |
| **Lumbar Spine Series** | 1.80           | 5.0      |
|                         | (3.6–12.6)     | (5.4–43.2) |
| **AP Pelvis**           | 0.70           | 1.9      |
|                         | (1.4-7.0)      | (1.4-7.0) |
| **Barium meal**         | 3.00           | 11.5     |
|                         | (6.0-30)       | (7.8-123) |
| **Barium enema**        | 7.00           | 19       |
|                         | (14 – 70)      | (18.2-287) |
| **Coronary Angiogram**  | 10.2 (avg)     | 39       |
|                         | (19.4 – 58.1)  | (21.4-176) |
|                         | 3.6 y          | 13.9     |
|                         | (6.9– 20.8) y  | (7.6– 62.9) |
|                         | 1.5 (0.75 –6.0) y |
|                         | 26 (5.2 – 46) d |
|                         | 1.5 (0.75 – 6.0) y |
|                         | 3.9 (1.9 – 14.4) y |
|                         | 1.5 (0.75 – 5.0) y |
|                         | 10.7 (2.8 – 44) y |
|                         | 15 (6.5 – 102.5) y |