Consequences of modern anthropometric dimensions for radiographic techniques and patient radiation exposures

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(Received 11 October 2007; revised 2 June 2008; accepted for publication 3 June 2008; published 17 July 2008)

Radiographic techniques are devised on the basis of anatomic dimensions. Inaccurate dimensions can cause radiographs to be exposed inappropriately and patient radiation exposures to be calculated incorrectly. The source of anatomic dimensions in common usage dates back to 1948. The objective of this study was to compare traditional and modern anthropometric data, use modern dimensions to estimate potential errors in patient exposure, and suggest modified technique guidelines. Anthropometry software was used to derive modern anatomic dimensions. Data from routine annual testing were analyzed to develop an x-ray generator output curve. Published tabulated data were used to determine the relationship between tissue half-value layer and kilovoltage. These relationships were used to estimate entrance skin exposure and create a provisional technique guide. While most anatomic regions were actually larger than previously indicated, some were similar, and a few were smaller. Accordingly, exposure estimates were higher, similar, or lower, depending on the anatomic region. Exposure estimates using modern dimensions for clinically significant regions of the trunk were higher than those calculated with traditional dimensions. Exposures of the postero-anterior chest, lateral chest, antero-posterior (AP) abdomen, male AP pelvis, and female AP pelvis were larger by 48%, 31%, 54%, 52%, and 112%, respectively. The dimensions of bony regions of the anatomy, such as the joints and skull, were unchanged. These findings are consistent with the idea that anatomic areas where fat is deposited are larger in the modern U.S. population than they were in previous years. Exposure techniques for manual radiography and calculations of patient dose for automatic exposure control radiography should be adjusted according to the modern dimensions. Population radiation exposure estimates calculated in national surveys should also be modified appropriately. © 2008 American Association of Physicists in Medicine.

[DOI: [10.1118/1.2952361](https://doi.org/10.1118/1.2952361)]

Key words: anthropometric dimensions, radiographic technique, radiation exposure, NEXT

I. INTRODUCTION

Radiographic technique guides are used by technologists to correctly expose image receptors and produce diagnostic-quality radiographic projections. In theory, technique guides are devised by determining the exposure settings that will result in the best images within a reasonable exposure time while minimizing patient radiation dose. These values are based on the exposure required at the image receptor, the attenuation that x-rays experience in transit to the receptor from interactions with the patient and imaging apparatus, the initial quantity and quality of x rays produced by the generator, and the dispersion of x-rays according to the inverse-square of the distance from the focal spot. Attenuation depends on the quality of the x-ray beam, represented by the kilovolts-peak (kVp) and the half-value layer (HVL), but also directly on the thickness of the anatomic region imaged, hence, regional thicknesses are important for determining appropriate exposure techniques.

Traditionally, technique guides have been created using adult body part thicknesses reported by Fuchs in 1948.¹ The

fundamental premise of Fuchs' work was that the majority of the adult population could be appropriately imaged using radiographic techniques selected for average dimensions. Fuchs' work is the basis of simplified technique selection which does not require the measurement of actual individual patient body part thickness. Our hypothesis was that the dimensions of the modern American population are, on average, larger than the dimensions determined by Fuchs. The use of fixed techniques based on the traditional anatomic dimensions could result in underexposed radiographs. Correcting for this would either lead to an increase in the number of repeated examinations or an increase in routine fixed technique settings, both of which could result in higher than anticipated radiation doses to patients.^{2,3} When automatic exposure control (AEC) of the x-ray system is used, underexposure of the image receptor is not a problem. AEC runs the x-ray generator longer to compensate for larger patients. However, if smaller dimensions are assumed for average-sized adult patients, radiation exposures to patients will be underestimated.

The purpose of this work was to compare the traditional and modern anthropometric data, use modern dimensions to estimate potential errors in patient radiation exposure, and suggest modified technique guidelines.

II. MATERIALS AND METHODS

II.A. Anthropometric data

A table of adult body part thicknesses, originally created by Fuchs,¹ was updated with modern data using PeopleSize 2000 Pro (Open Ergonomics, Leicestershire, U.K.).⁴ This program reports anthropometric data on the basis of user-specified anatomic regions and percentile ranges for a variety of populations and age groups, including the U.S. adult population.⁵ The U.S. data were collected and recalculated from several sources, including the Third National Health and Nutrition Survey (NHANES-III), conducted from 1988 to 1994, by the National Center for Health Statistics of the U.S. Centers for Disease Control and Prevention (CDC).⁶

The dimensions used for this study were obtained from PeopleSize using the modern U.S. adult (age 18–64 years) population, with a female-to-male ratio of 51:49. For each anatomic region, Fuchs' dimensions were analyzed to determine the proportion of the modern population included. A new thickness range was then generated corresponding to the proportion of the population Fuchs had intended to include. The 50th percentile measurement was found as well. Anteroposterior (AP) dimensions were approximated for the upper arm, lower leg, and neck using circumferences. Similarly, lateral (LAT) dimensions were approximated from circumferences for the upper arm, lower leg, and thigh. AP wrist dimensions were approximated by considering the circumference of the body part to be the perimeter of a rectangle, using the LAT dimension, which is reported by PeopleSize, for two sides of the rectangle. The thickness data for a few anatomic regions were not specified in PeopleSize, hence, these measurements were not updated.

II.B. Composite output curve

Radiation output data were obtained from annual compliance testing performed on five model XQ/i and two model XR/d clinical x-ray systems (GE Healthcare, Milwaukee, WI). A calibrated ion chamber was placed at a specified distance from the x-ray tube to measure exposure in mR, and a noninvasive voltage divider was positioned in the beam path to measure kVp. Exposures were measured at several kVps, divided by the tube current-time product (mA s), and normalized to a distance of 1 m using the inverse-square law. Data were pooled from large and small focal spot tests on all seven machines, and output in mR/mA s at 1 m was plotted versus kVp. A second-order polynomial, fitted to the data using Microsoft Excel (Microsoft Corp., Redmond, WA), served as the composite output model.

II.C. Tissue half-value layer

The relationship between tissue HVL and kVp was determined as described by Willis and Parker.⁷ A linear model

relating beam HVL (mm Al) to kVp and a quadratic model relating tissue HVL (cm) to beam HVL were obtained from data tables in NCRP Report 102,⁸ which are based on attenuation in water. The combination yielded a second-order polynomial relating tissue HVL to kVp.

II.D. Entrance skin exposure

A Philips Technique Guide⁹ was used to determine typical kVp values for each anatomic region. Source-to-image distances (SID) were taken from industry standards: 183 cm (72 in.) for chest examinations and 102 cm (40 in.) for all other examinations. The tissue HVL was calculated from the kVp using the polynomial described above. This approach provided unrealistic values for the thorax, which contains more air than other regions of the body. The chest tissue HVL was instead calculated using attenuation data from a LucAl chest phantom,¹⁰ which simulates a 23-cm adult chest. Bucky factors were calculated from previous tests using 12:1 antiscatter grids focused for 183 and 102 cm SIDs at 125 and 80 kVp with LucAl chest and abdomen¹¹ phantoms, respectively. An image receptor exposure of 1 mR was assumed, corresponding roughly to that required for a 200 speed class film-screen receptor. The kVp, tissue HVL, and Bucky factor were used to calculate the amount of radiation that would have reached the receptor had the patient not been in the beam, henceforth referred to as the unattenuated receptor exposure (URX). For each projection, the URX was corrected from the receptor plane to the plane of entry into the patient, including the appropriate distance from the patient support to the receptor plane, using the inverse-square law, yielding the free-in-air entrance skin exposure (ESE). ESE was calculated for both Fuchs' and modern dimensions. The calculated ESEs were compared with the radiographic entrance exposure limits specified by the State of Texas.¹²

II.E. Provisional technique guide

A fixed kVp technique guide was developed on the basis of modern dimensions. For each radiographic view, the URX was corrected using the inverse-square law to a distance of 1 m from the radiation source. The generator output at 1 m in mR/mAs was determined from the composite output curve and the kVp selected for the specific radiographic view. The amount of radiation required at 1 m was divided by the generator output to calculate the mAs necessary for an appropriately exposed radiograph of an average-sized patient.

To assess the applicability of the recommended techniques, a 1-HVL-wide thickness range was determined by adding and subtracting half a tissue HVL to the median thickness for each anatomic region. This was assumed to be the range of thicknesses for which a patient could be radiographed with the recommended technique without under- or overexposing the receptor. Each range corresponds to a receptor exposure between 0.7 and 1.4 mR. The proportion of the population represented by each range was determined from PeopleSize.

The recommended techniques were also compared with published computed radiography technique guidelines based

TABLE I. Comparison of modern body part thicknesses to traditional values.

Anatomic region	View ^a	Fuchs' dimensions, 1948			Modern dimensions			Change in median thickness (%)
		Median thickness ^b (mm)	Thickness range (mm)	Incidence ^c (%)	Median thickness ^b (mm)	Thickness range (mm)	Incidence ^c (%)	
Fifth finger	AP/PA	28	15–40	34	14	11–18	99	–50
	LAT	28	15–40	63	16	12–19	99	–43
Third finger	AP/PA	28	15–40	91	17	13–22	99	–39
	LAT	28	15–40	99+	19	15–24	99	–32
Thumb	AP/PA	28	15–40	88	17	13–23	99	–39
	LAT	28	15–40	99+	21	16–27	99	–25
Hand	AP/PA	40	30–50	20	56	41–74	99	+40
	LAT	85	70–100	52	100	84–116	93	+18
Wrist	AP/PA*	45	30–60	92	36	29–51	99	–20
	LAT	65	50–80	83	55	45–66	98	–15
Elbow	LAT	80	70–90	59	71	64–80	87	–11
Upper arm	AP*	85	70–100	48	100	75–136	95	+18
	LAT*	85	70–100	48	100	76–134	94	+18
Foot	AP/PA	70	60–80	69	75	63–90	92	+7
	LAT	80	70–90	15	97	85–108	91	+21
Ankle	LAT	75	60–90	99	72	61–84	96	–4
Leg	AP*	110	100–120	36	124	106–150	85	+13
	LAT*	100	90–110	14	124	104–154	89	+24
Knee	LAT	105	90–120	93	102	89–114	92	–3
Thigh	AP	155	140–170	41	169	140–208	77	+9
	LAT*	145	130–160	2	196	174–227	76	+35
Vertebrae C1–C3	AP*	130	120–140	50	123	110–138	77	–5
Vertebrae C4–C7	AP*	125	110–140	79	123	100–154	98	–2
Cervical spine	LAT	115	100–130	37	136	110–171	90	+18
Thoracic spine	AP	220	200–240	15	271	235–321	76	+23
	LAT	300	280–320	35	327	283–372	81	+9
Lumbar spine	AP	200	180–220	38	224	194–254	69	+12
	LAT	295	270–320	52	288	234–326	77	–2
Pelvis (F)	AP	210	190–230	22	253	216–312	78	+20
Pelvis (M)	AP	210	190–230	42	234	210–263	78	+11
Skull	PA	195	180–210	82	191	171–212	96	–2
	LAT	155	140–170	90	150	138–162	88	–3
Sinuses-frontal	PA	195	180–210	82	191	170–213	97	–2
Sinuses-maxillary	PA	200	180–220	96	197	183–213	88	–2
Sinuses	LAT	150	130–170	99	150	135–166	96	0
Mandible	LAT	110	100–120	78	110	100–121	82	0
Chest	PA	225	200–250	25	271	231–329	82	+20
	LAT	295	270–320	39	327	280–376	84	+11

^aAn asterisk indicates projections for which dimensions were approximated from PeopleSize using circumferences because direct measurements were unavailable.

^bFor Fuchs' dimensions, the median is the center of the range given. For modern dimensions, the median is the 50th percentile measurement.

^cThe incidence is the proportion of the modern population that the thickness range includes.

on traditional dimensions.^{2,3} The composite output model was used to calculate exposure at 1 m from the x-ray source using the kVp and mAs values specified in each set of techniques, after which a correction to 200 speed class was made to facilitate comparison. The resultant exposure from each set was compared to determine whether the recommended exposures were similar for each guide's assumption of an average-sized patient.

II.F. Clinical validation

In order to test the validity of underlying assumptions in our exposure and attenuation models, ten clinical examina-

tions each of AP abdomen and PA chest were selected at random from two x-ray systems. Patient thickness was determined retrospectively from the LAT view of each chest examination and from computed tomography studies of each patient for the abdomen views. All chest views were acquired at 125 kVp and 183 cm SID using AEC at 250 speed class and all abdomen views were acquired at 80 kVp and 102 cm SID using AEC at 400 speed class. The receptor exposure was assumed to be 0.62 mR for the chest exams and 0.39 mR for the abdomen exams, which corresponds to data from the manufacturer for AEC exposures with the appropriate fixed focus grid at these speed classes, confirmed

FIG. 1. Composite output curve. A second-order polynomial fit of pooled data from seven clinical x-ray generators. Coefficients for the polynomial are listed in Table II. Note that the composite function represents the data well ($r^2=0.993$).

by previous measurements with the LucAl chest and abdomen phantoms under the same conditions. Using our assumptions, we calculated the expected mAs for each examination and compared it to the mAs actually delivered. In a manner described below for estimation of HVL for the LucAl chest phantom, we also calculated the effective tissue HVL from the patient thickness and mAs delivered.

III. RESULTS

III.A. Anthropometric data

Table I shows the comparison between the new anthropometric data obtained from PeopleSize and Fuchs' data. No dimensions were found in PeopleSize for the forearm, shoulder, clavicle, hip, AP elbow, or AP ankle. Thus, these views were not updated. The modern data revealed larger dimensions for several body parts, including the chest, pelvis, AP abdomen (used for the AP lumbar spine), and LAT neck (used for the cervical spine). Larger dimensions were also indicated for the extremities, including the upper arm, thigh, lower leg, and foot.

Thickness data for some regions were similar to or smaller than the traditional data. The measurements of the skull, leg joints, and elbow remained comparable to previous measurements. These are areas of the body where fat deposition is not expected. The mean finger size was smaller, mainly because of the unrealistically large upper bound of 4 cm reported by Fuchs for all fingers. The tissue thicknesses for the wrist, AP neck, and LAT abdomen (used for the LAT lumbar spine) were also smaller, by 15%–20%, 2%–5%, and 2%, respectively.

FIG. 2. Tissue HVL as a function of tube potential. The curves indicate the thickness of tissue required to attenuate an x-ray beam to half its initial intensity. The relationship, shown for 15×15 cm (solid line) and 35×35 cm (broken line) field sizes, is a quadratic polynomial based on tabulated data from NCRP-102 according to the method of Willis and Parker (Ref. 7). Coefficients for the polynomial are listed in Table II.

III.B. Composite output curve

The composite output curve is shown in Fig. 1. In the pooled data, the standard deviation of output at each kVp was less than 5%. A second-order polynomial model fit the data well, producing a fit with a correlation coefficient of 0.9932. Coefficients for the polynomial and their associated errors are listed in Table II. The mean HVL measured at 80 kVp for the seven systems was 3.53 ± 0.15 (4.3%) mm Al. This output model should serve as a reasonably good predictor of output for other modern three-phase or high-frequency x-ray generators.

III.C. Tissue HVL

The curves relating tissue HVL to kVp are shown in Fig. 2. The models were derived from two previous fits to data, as explained in the Sec. II C. Thus, no measured data are shown, but the relationship determined between these two variables for different field sizes is illustrated. Coefficients for the polynomials are listed in Table II. This relationship should hold true for body parts that are water equivalent. The thorax, for example, contains air: therefore, it has a different tissue HVL. The appropriate field size was selected according to the size of the anatomic area being imaged.

III.D. Entrance skin exposure

Tests with the LucAl chest phantom showed transmissions of 0.133, 0.144, and 0.191 for 75, 80, and 125 kVp, respec-

TABLE II. Polynomial coefficients.

$f(x); x=\text{kVp}$	ax^2	bx	c
Output (mR/mAs @ 1 m)	$4.95 \times 10^{-4} \pm 20.2\%$	$7.90 \times 10^{-2} \pm 23.2\%$	$-2.86 \pm 27.6\%$
Tissue HVL (15×15 cm)	-2.22×10^{-4}	6.29×10^{-2}	6.24×10^{-1}
Tissue HVL (35×35 cm)	1.83×10^{-4}	6.50×10^{-2}	6.76×10^{-1}

TABLE III. Exposure estimates and provisional technique guide.

Anatomic region	Exam ^a	kVp	Fuchs' dimensions, 1948		Modern dimensions		Change in ESE ^b (%)
			ESE (mR)	Exposure (mAs)	ESE (mR)	mAs	
Fifth finger	AP/PA	45	2	1.16	1	0.84	-30
	LAT	45	2	1.16	1	0.88	-26
Third finger	AP/PA	45	2	1.16	2	0.90	-24
	LAT	45	2	1.16	2	0.94	-20
Thumb	AP/PA	45	2	1.16	2	0.90	-24
	LAT	45	2	1.16	2	0.99	-16
Hand	AP/PA	45	3	1.53	4	2.21	+49
	LAT	45	8	4.31	12	6.09	+46
Wrist	AP/PA	45	3	1.72	2	1.39	-20
	LAT	45	5	2.72	4	2.16	-22
Elbow	LAT	50	7	2.49	5	2.05	-19
Upper arm	AP	65	25	4.54	33	5.84	+33
	LAT	65	25	4.54	33	5.84	+33
Foot	AP/PA	45	5	2.73	6	3.04	+13
	LAT	45	7	3.39	10	4.88	+49
Ankle	LAT	50	6	2.23	5	2.09	-7
Leg	AP	60	9	1.98	12	2.53	+32
	LAT	60	7	1.66	12	2.53	+61
Knee	LAT	60	8	1.81	7	1.70	-7
Thigh	AP	70	84	11.2	109	14.0	+30
	LAT	70	70	9.51	180	21.5	+157
Vertebrae C1-C3	AP	65	59	9.66	52	8.59	-13
Vertebrae C4-C7	AP	65	54	8.88	52	8.59	-4
Cervical spine	LAT	65	44	7.51	66	10.7	+50
Thoracic spine	AP	75	57	5.58	103	8.72	+80
	LAT	80	130	8.96	177	11.3	+36
Lumbar spine	AP	75	170	17.5	261	25.2	+54
	LAT	90	592	33.2	527	30.2	-11
Pelvis (F)	AP*	80	179	15.8	379	29.9	+112
Pelvis (M)	AP*	80	179	15.8	272	22.6	+52
Skull	PA	75	155	16.2	144	15.2	-7
	LAT	65	95	14.7	87	13.5	-9
Sinuses-frontal	PA	70	177	21.2	164	19.9	-7
Sinuses-maxillary	PA	70	194	23.0	184	21.9	-5
Sinuses	LAT	70	77	10.3	77	10.3	0
Mandible	LAT*	80	32	3.63	32	3.63	0
Chest	PA	125	17	2.81	25	3.91	+48
	LAT	125	31	4.64	40	5.85	+31

^aAn asterisk indicates that the kVp for this examination was obtained from FujiFilm exposure recommendations because it was not specified in the Philips technique guide.

^bPercentage changes were calculated from original ESEs before rounding.

tively. HVLs were calculated according to the following equations, in which I/I_0 is the transmission, x is the path-length, and μ is the linear attenuation coefficient,

$$\frac{I}{I_0} = e^{-\mu x}, \quad (1a)$$

$$\text{HVL} = \frac{\ln 2}{\mu}. \quad (1b)$$

Tissue HVLs for the AP thoracic spine, LAT thoracic spine, and PA/LAT chest examinations were determined to be 7.91, 8.23, and 9.33 cm, respectively.

Bucky factors used for the overall attenuation calculation were 1.0 for examinations performed without an antiscatter grid, 4.6 for all other examinations performed with a grid at a SID of 102 cm, and 2.45 for examinations performed with a grid at a SID of 183 cm. No grids are to be used in examinations of the fingers, hands, wrists, forearms, elbows, feet, ankles, lower legs, or knees. PA and LAT chest examinations are to be performed at 183 cm with a grid. All other examinations are to be performed at 102 cm with a grid.

Table III presents ESEs calculated for both traditional and modern dimensions. ESEs estimated for a few anatomical regions, including the fingers, wrists, and elbows, were actu-

TABLE IV. Comparison with exposure limits.

Anatomic region	Exam	Texas ESE limits		Modern dimensions		
		Patient thickness (cm)	ESE limit (mR)	Patient thickness (cm)	Calculated ESE (mR)	Calculated vs limit (%)
Chest	PA	23	30	27.1	25	-17
Abdomen	KUB	23	450	22.4	261	-42
Lumbo-sacral spine	AP	23	550	22.4	261	-53
Cervical spine	AP	13	120	12.3	52	-57
Thoracic spine	AP	23	325	27.1	103	-68
Full spine	AP	23	300	27.1	196	-35
Skull	Lat	15	150	15	87	-42
Foot	AP	8	50	7.5	6	-88

ally less than those calculated using the traditional dimensions. ESEs estimated using modern dimensions were similar to those using traditional dimensions for several regions, such as those for the skull, ankle, knee, AP neck, AP foot, and LAT abdomen. However, for most regions, ESEs calculated using the modern dimensions were much higher than those calculated using traditional dimensions. These regions included the hand, upper arm, lower leg, thigh, thoracic spine, pelvis, chest, LAT foot, LAT neck, and AP lumbar spine. ESEs estimated for modern dimensions of the PA chest, LAT chest, AP abdomen, male AP pelvis, and female AP pelvis were larger by 48%, 31%, 54%, 52%, and 112%, respectively, than were those calculated using traditional dimensions.

Table IV displays the regional thicknesses assumed and exposure limits for the radiographic examinations for which the State of Texas specifies radiographic entrance exposure limits. For comparison, the modern thicknesses and corresponding ESEs determined in this study are also shown. For each of these examinations, the calculated ESE was below the exposure limit mandated by the State.

III.E. Provisional technique guide

Table III also shows the mAs required to sufficiently expose the receptor for a modern average-sized patient, based on our assumptions of output and attenuation, as described above. Techniques were calculated to deliver 1 mR exposure to the image receptor. These calculated values are provided for illustration purposes only: the utility of these techniques for clinical radiography is contingent on clinical validation with actual patients and will vary depending on differences in x-ray generator and image receptor functional characteristics.

Table V shows the 1-HVL-wide range for each anatomic region, which represents the thickness range for which the recommended techniques will produce a correctly exposed radiograph. The majority of these ranges encompassed a large proportion of the population. However, there were nine regions for which the range described less than 80% of the population: the AP and LAT thigh, LAT cervical spine, AP and LAT thoracic spine, AP and LAT lumbar spine, and male

and female AP pelvis. Modification of the recommended technique according to measurements of actual anatomic characteristics will be more important for these views.

Table V also displays a comparison of the exposures produced by the techniques used in this study and those suggested for our median dimensions according to published techniques,^{2,3} adjusted for speed class and SID. In every case except the upper arm (humerus), our suggested techniques resulted in less exposure than the published techniques. The reduction of exposure ranged from 9% to 91% compared to the published techniques. These differences reflect a number of factors including a higher output in mR/mAs for our composite output curve compared to the output curve used to derive the published techniques, different kVps for the examinations, and a different attenuation model.

III.F. Clinical validation

Table VI shows the results of our clinical validation. The average patient thicknesses for the abdomen ($25.1 \text{ cm} \pm 19\%$) and chest ($26.5 \text{ cm} \pm 12\%$) exams compare favorably with our median modern dimensions for the same views (22.4 and 27.1 cm, respectively). The variation in the mAs delivered was 2–4 times greater than the variation in patient thickness. The tissue HVL calculated for the abdomen was $4.42 \text{ cm} \pm 9.9\%$ and for the chest was $9.77 \text{ cm} \pm 16\%$, as compared to the values of 4.70 and 9.33 cm that we assumed in our attenuation model. The calculated ESE and mAs needed from our model also varied 2–4 times more than the variation in patient thickness. The errors between the actual mAs delivered and the calculated mAs needed had a standard deviation of about 30%. A better correlation between mAs delivered and mAs needed was observed for abdomen ($r^2=0.7333$) as opposed to chest exams ($r^2=0.4676$). It is apparent from these results that factors other than body part thickness affect the attenuation of radiation by real patients, such as degree of inspiration, body habitus, positioning, and collimation. These clinical examples are not intended to serve as complete clinical validation of the provisional technique guide but suggest that our output and attenuation models are appropriate.

TABLE V. Applicable thickness ranges and exposure comparison.

Anatomic region	Applicability		Exposure comparison		
	1-HVL wide thickness range (mm)	Incidence (%)	Output from provisional technique (mR@1 m)	Output from published technique ^a (mR@1 m)	Change from published technique (%)
Fifth finger (AP/PA)	1–29	~100	1.4	—	—
Fifth finger (LAT)	1–31	~100	1.5	—	—
Third finger (AP/PA)	2–32	~100	1.5	—	—
Third finger (LAT)	4–34	~100	1.6	—	—
Thumb (AP/PA)	2–32	~100	1.5	—	—
Thumb (LAT)	6–36	~100	1.7	—	—
Hand (AP/PA)	41–71	97.4	3.8	6.3*	–40
Hand (LAT)	85–115	90.2	10	11*	–9.2
Wrist (AP/PA)	21–51	~100	2.4	4.7*	–50
Wrist (LAT)	40–70	99.89	3.7	9.6*	–62
Elbow (LAT)	55–87	~100	4.8	15*	–68
Arm (AP)	79–121	84.2	25	12*	+120
Arm (LAT)	79–121	84.2	25	16*	+57
Foot (AP/PA)	59–91	96.8	5.2	8.8*	–41
Foot (LAT)	81–113	98.5	8.3	10*	–61
Ankle (LAT)	56–88	99.6	4.9	12*	–60
Leg (AP)	104–144	81.9	9.3	12*	–34
Leg (LAT)	104–144	81.9	9.3	14*	–23
Knee (LAT)	82–121	99.1	6.2	15*	–58
Thigh (AP)	147–191	59.2	71	240*	–70
Thigh (LAT)	174–218	68.7	110	380*	–71
Vertebrae C1–C3 (AP)	102–144	93.6	38	70*	–46
Vertebrae C4–C7 (AP)	102–144	93.6	38	70*	–46
Cervical spine (LAT)	115–157	75.0	47	93*	–50
Thoracic spine (AP)	231–311	74.7	51	520*	–90
Thoracic spine (LAT)	286–368	77.1	75	840*	–91
Lumbar spine (AP)	201–247	56.4	150	270	–44
Lumbar spine (LAT)	263–313	50.4	250	930*	–73
Pelvis (AP) (Female)	229–277	50.7	200	400*	–50
Pelvis (AP) (Male)	210–258	74.4	150	400*	–62
Skull (PA)	168–214	98.0	89	180	–50
Skull (LAT)	129–171	99.5	59	80	–26
Sinuses-frontal (PA)	169–213	97.4	100	160	–37
Sinuses-maxillary (PA)	175–219	97.7	110	180	–37
Sinuses (LAT)	128–172	99.6	53	60	–13
Mandible (LAT)	86–134	99.6	24	—	—
Chest (PA)	223–319	82.4	58	37*	–38
Chest (LAT)	279–375	84.6	86	150*	–43

^aAn asterisk indicates technique selected for modern median thickness.

IV. DISCUSSION

Discrepancies between modern anthropometric dimensions and traditional dimensions are consistent with the notion that anatomic areas where fat is deposited are larger in the modern U.S. population than in previous years' populations. For bony anatomic areas, such as joints, the dimensions were unchanged. The few regions with smaller modern dimensions were either not substantially different or represent a refinement in data, such as the upper dimension bound for the fingers. Regions that were larger included clinically significant areas of the trunk that are frequently imaged and contain radiosensitive organs. Although this study was spe-

cific to the modern U.S. adult population, the method could be extended to other populations for which anthropometric data are available.

We used the PeopleSize anthropometric model for the U.S. population in an attempt to simulate Fuch's description of anatomic dimensions that would be representative of a large segment of the population. For any particular anatomic region, the actual size distribution within the population is not necessarily symmetric. The software developer points out that, especially for fatty body parts, the median is not representative of the average. Our use of the terms "average" and "mean" are not strictly true for the distribution, rather they

TABLE VI. Clinical validation of output and attenuation.

AP abdomen						
Patient	AP thickness (cm)	mAs delivered	Tissue HVL calculated (cm)	ESE (mR)	mAs needed	Error (%)
1	30.3	19	4.99	355	24.6	29
2	24.6	14.65	4.31	130	10.6	-28
3	32.2	30.9	4.75	498	32.5	5
4	21.4	9.78	4.18	75	6.6	-32
5	26.3	18.7	4.34	176	13.6	-27
6	25.4	22.75	4.01	150	11.9	-48
7	27.3	21.69	4.36	209	15.8	-27
8	15.7	5.59	3.64	28	2.9	-49
9	21.9	5.62	5.07	81	7.1	27
10	25.7	14.32	4.53	158	12.5	-13
Average	25.1	16.3	4.42	186	14	-16
SD	19%	49%	9.9%	76%	64%	28

PA chest						
Patient	AP thickness (cm)	mAs delivered	Tissue HVL calculated (cm)	ESE (mR)	mAs needed	Error (%)
1	27.3	3.92	7.79	15.8	2.5	-37
2	26.6	2.7	8.96	14.9	2.3	-13
3	23.6	1.5	11.13	11.5	1.9	26
4	23	1.72	9.92	10.9	1.8	5
5	28.9	4.9	7.55	18.1	2.8	-44
6	24.4	2.22	9.08	12.3	2.0	-10
7	32	3.97	9.08	23.6	3.5	-13
8	27.3	2.17	10.29	15.8	2.5	13
9	21.9	1.22	12.02	10.0	1.7	37
10	29.7	1.95	11.88	19.4	2.9	50
Average	26.5	2.63	9.77	15.2	2.38	1.3
SD	12%	47%	16%	28%	24%	31

are the average of the thicknesses at the extremes encompassing the incidence we chose.

The differences found in the anthropometric data have consequences for radiographic imaging practice and patient radiation exposures. Radiography of the trunk using manual techniques based on traditional average adult dimensions will result in underexposure of the image receptor. After thorough clinical validation, the proposed techniques will address this problem. Radiographic imaging of the trunk using AEC will compensate for the larger dimensions with longer exposure times, which increase the possibility of patient motion and will likewise involve higher patient radiation exposures.

The use of a single Bucky factor for all exams is an oversimplification. In order to assess the error introduced by this approximation, we have attempted to determine the degree of variation in its value. For example, Table B.4 of NCRP Report No. 102 (Ref. 8) indicates that for reasonably typical grid ratios (6:1 to 12:1), as the kVp increases from 70 to 120 kVp, the Bucky factor increases only between 6% and 25% for a particular grid ratio and only 52% from the lowest kVp and lowest grid ratio to the highest kVp and the highest grid ratio. In our study, the nonchest grid exams included pelvis

and L-spine acquired between 75 and 90 kVp, with 12:1 grids, so the difference would likely be less than 10%. This opinion is supported by Fig. 6–28 of Ref. 13, which shows the variation in Bucky factor versus kVp for a variety of grid ratios using a 30 cm water phantom, as determined by computer simulation.

The conventional method for determining Bucky factor involves a wide x-ray field and a specific scattering media, usually a 20 cm water phantom. Our value for the Bucky factor was the average between that indicated by an ion chamber placed under a LucAl abdomen with and without the grid, and the value indicated by the mAs delivered with and without the grid. The second measurement used a correction factor of 0.83 provided by the manufacturer for a reduction of mAs delivered by the AEC when the grid is removed. This value was independently verified. There was good agreement between the Bucky values determined by the two methods, suggesting that the attenuation by the table, and AEC assembly of our system does not appreciably affect the apparent Bucky factor. We determined this value at 80 kVp for a phantom that approximates an average adult patient with appropriate wide collimation. Because the kVp and

simulated patient size are approximately midrange, we do not anticipate major variation in the scatter fraction or in the Bucky value for nonchest grid exams.

The State of Texas specifies ESE limits for a subset of views considered in this study. All ESEs calculated for these views were below the limits, even though the exposures for modern dimensions increased by as much as 80% over those for traditional dimensions. The dimensions specified in State regulations are consistent with modern dimensions, with the exception of chest thickness, for which the traditional average thickness is used.

The National Evaluation of X-ray Trends (NEXT) surveys are periodically conducted in collaboration between the Conference of Radiation Control Program Directors and the Food and Drug Administration's Center for Devices and Radiological Health.¹⁴ These surveys use phantoms to simulate the anatomy of interest in order to obtain ESE and image quality data. These data and the frequency of chest x-ray procedures in the United States are combined to estimate the population radiation exposure from these examinations. The chest phantoms used are LucAl chest phantoms, which are designed to simulate the attenuation and scatter properties of a 23-cm-thick chest. The data obtained in this study suggest that the median American chest thickness is 27 cm. The ESE to properly expose a 27-cm chest would necessarily be more than that to expose a 23-cm chest, by 43% according to our calculations. Therefore, estimates of population radiation exposure based on data from a phantom that approximates 23 cm likely underestimates the exposure by 43%.

The abdomen and lumbar spine NEXT studies are performed using the LucAl abdomen phantom which simulates a 21-cm-thick adult abdomen, which is intermediate between the Fuchs' dimension of 20 cm and the PeopleSize dimension of 22.4 cm. The ESE reported by the 1995 study was 370 mR, which is somewhat higher than the 261 mR ESE calculated for our modern dimensions, but well within the large standard deviation of the NEXT measurements (± 229 mR). The ESE to properly expose a 22.4 cm lumbar spine would necessarily be more than that to expose a 21 cm lumbar spine, by 29% according to our calculations. Therefore, estimates of population radiation exposure based on data from a phantom that approximates 21 cm likely underestimates the exposure by 29%.

The American Association of Physicists in Medicine Task Group No. 7 has recommended reference values (RVs) for some diagnostic x-ray examinations based in part on NEXT data.¹⁵ These recommendations have been incorporated into a practice guideline by the American College of Radiology for diagnostic reference levels (DRLs).¹⁶ The purpose of DRLs is to establish exposure levels for standardized examinations that trigger further attention when exceeded. The standardized examinations are based on measurements of exposure using phantoms approximating average adult dimensions, so RVs and DRLs should be reevaluated considering the dimensions of modern patients. The RVs for the PA view of the chest, AP view of the cervical spine, AP view of the abdomen, and AP view of the lumbar spine are 25, 125, 450,

and 500 mR, respectively. The DRL for the PA view of the chest is also 25 mR and the DRL for the AP view of the abdomen is 600 mR, however, these values are specified for screen-film receptors only. In our study, none of the RVs or DRLs was exceeded by ESEs calculated for modern dimensions shown in Table IV. None of the ESEs calculated for patients in the clinical validation (Table VI) exceeded the RVs or DRLs. It is important to note that the examinations in the clinical validation were performed using a digital detector that requires less exposure than the provisional technique guide in Table III.

The techniques presented in this work should be applicable to more than 80% of the population for all but nine examinations. For these examinations, patients should be measured and mAs adjusted accordingly. The techniques presented here resulted in lower patient exposures than did the published techniques for the majority of the examinations, regardless of whether those regions are now larger, similar, or smaller in thickness than indicated by traditional data. Our ESE estimates for the published techniques were adjusted to correct for differences in kVp and receptor speed class, but used our models for the composite output curve and attenuation by the patient and grid. We are aware of a discrepancy between the output curve described in our study and that used to determine the published techniques. The latter indicates output that is from 24% to 14% lower than that suggested by the composite output model from our work for kVps between 60 and 130. The difference in output may reflect a difference in HVL, however, lower output from added filtration would tend to decrease the attenuation of the beam by the patient, meaning that less mAs would be needed to produce the same exposure at the image receptor which is not what our results suggest. The lower output curve could reflect more generator voltage ripple, different generator type, or a different x-ray tube. Assuming similar HVL, a lower output curve requires more mAs to be delivered to produce the same exposure to the image receptor. Hence, the published mAs values are very high for certain examinations such as those for the AP and LAT lumbar spine and LAT thoracic spine, which results in higher calculated exposures using our output curve. These high mAs recommendations may be the result of clinical validation in the authors' clinical setting. The published techniques for the PA chest produce a lower exposure because they were based on a chest thickness of 22 cm rather than 27 cm. Adjusting their mAs according to their directions for +5 cm (8.34 mAs) produces an exposure 60% higher than our suggested technique. Note that their recommendation of 106 kVp is also much lower than our suggestion of 125 kVp and will result in lower transmission through the patient necessitating a higher ESE. Their published average thickness for the lateral view of the chest is closer to our value, and their recommended kVp is also closer to ours: therefore, the ESEs are approximately the same. It is important to note that the published techniques were based on their experimental measurements of attenuation in water for all body parts, including the thorax, whereas our chest techniques were based on attenuation in a patient-equivalent phantom. For body parts other than the thorax,

our techniques depended on an attenuation model derived from tabulated values of attenuation in water. Furthermore, our specific attenuation function was selected according to the field size appropriate to the body part, while the published techniques were based on measurements with a single constant field size for all body parts.¹⁷

The National Center for Health Statistics of the U.S. CDC has conducted biennial NHANES surveys conducted since 1999, although there was no indication that this data had been incorporated into the PeopleSize 2000 software. It is possible that there have been changes in U.S. adult population dimensions since the data that was available to us in a convenient form. Future work should determine whether important differences exist between the most current data and that on which our study was based.

V. CONCLUSIONS

Modern anthropometric data from PeopleSize 2000 Pro indicate that the thicknesses of most anatomic regions of modern U.S. adults differ from those reported by Fuchs in 1948.¹ In general, bony areas such as the skull and extremity joints are similar or smaller in thickness. However, many frequently radiographed regions of the trunk, such as the chest, abdomen, and pelvis, are larger. A comparison of ESEs calculated with both the modern and traditional dimensions reveals many large differences, especially for clinically significant regions. Using older dimensions to estimate population radiation exposure and establish patient radiation exposure limits may yield invalid results. Modern anthropometric data can be used to refine estimates of population radiation exposure and validate estimates for those anatomic regions that have not changed. The modern data have been used to suggest mAs values for manual radiographic techniques. These suggestions should be clinically validated to create a technique guide. Even more recent anthropomorphic data exists than what was conveniently available to us; future work should determine whether important changes have been observed in U.S. adult dimensions since 1994.

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