LINEAR DIMENSIONS AND VOLUMES OF HUMAN LUNGS OBTAINED FROM CT IMAGES

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Abstract—**This work provides the results of a collaboration between the Human Monitoring Laboratory (HML) and the Centre Hospitalier de l'Université de Montréal (CHUM) in which CHUM provided CT lung image sets from 166 patients for the analysis of linear dimensions and lung volume. This work has shown that a large amount of data exists in the medical community that can be of value to the health physics community. The intent of this study was to determine the range of linear dimensional parameters that could be used for torso phantom development for males and females; understand and characterize the variability of linear lung dimensions for males and females; replace the brief table in ICRP 23 with more modern data for males and females; identify an empirical formula that would predict linear dimensions of human lungs from age, height and/or weight for males and females; characterize the left, right, and total lung volumes of males and females in this data set; and compare the lung volumes of males and females to published equations for determining lung volumes. It was found that linear dimensions of lungs are essentially independent of age, height, and weight, so predictive equations cannot be formulated; however, the ranges of those parameters have now been established for the population studied herein. The data presented here are more modern than the brief table that appeared in ICRP 23, and the average values could be used as future guidelines. Whole lung volumes have been determined from the voxel lung phantoms, and empirical formulae have been developed for males and females in this data set; these compare favorably with the published values in ICRP 66.**
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Key words: computed tomography; International Commission on Radiological Protection; lungs, human; phantom

INTRODUCTION

CONSTRUCTION OF phantoms to model the human torso has become much easier since the medical community has been employing imaging modalities such as computed tomography and magnetic resonance. The image sets obtained from such instruments can be used to reconstruct a three dimensional (3D) image of the scanned person with excellent definition of the internal structure. These 3D-image sets (voxel phantoms) can be used in computer simulation to model various aspects of radiation protection but can also be used as guidelines for constructing physical phantoms that can be used in subsequent experiments.

Some time ago, when trying to construct revised lung inserts (Kramer 2004) for the Lawrence Livermore National Laboratory's (LLNL) Torso Phantom, the Human Monitoring Laboratory (HML), which operates the Canadian National Calibration Reference Centre for Bioassay and In vivo Monitoring (Kramer and Limson Zamora 1994; Daka and Kramer 2009), tried to validate the shape of the lungs that were built.

While lung volumes have been studied in some detail, linear dimensions seemed hard to find. The International Commission on Radiological Protection's (ICRP) report on Reference Man (ICRP 1975) had one table giving some information about the sagittal diameter (or length), the transverse diameter at the base, and the anteroposterior diameter; however, in the revision of Reference Man (ICRP 2002), this information is missing. Similarly, the ICRP report on the Human Respiratory Tract (ICRP 1994), which gives detailed information about human lungs, fails to document the gross linear dimensions that would be useful for phantom designers.

This paper provides the results of a collaboration between the HML and the Centre Hospitalier de l'Université de Montréal (CHUM). CHUM provided CT lung image sets from 166 patients for analysis. The limitation of this work is that patients were asked to take a deep breath immediately prior to imaging. While this is not a full inflation of the lung, it does mean that the lung dimensions measured in this work are somewhat larger than the lung at rest.

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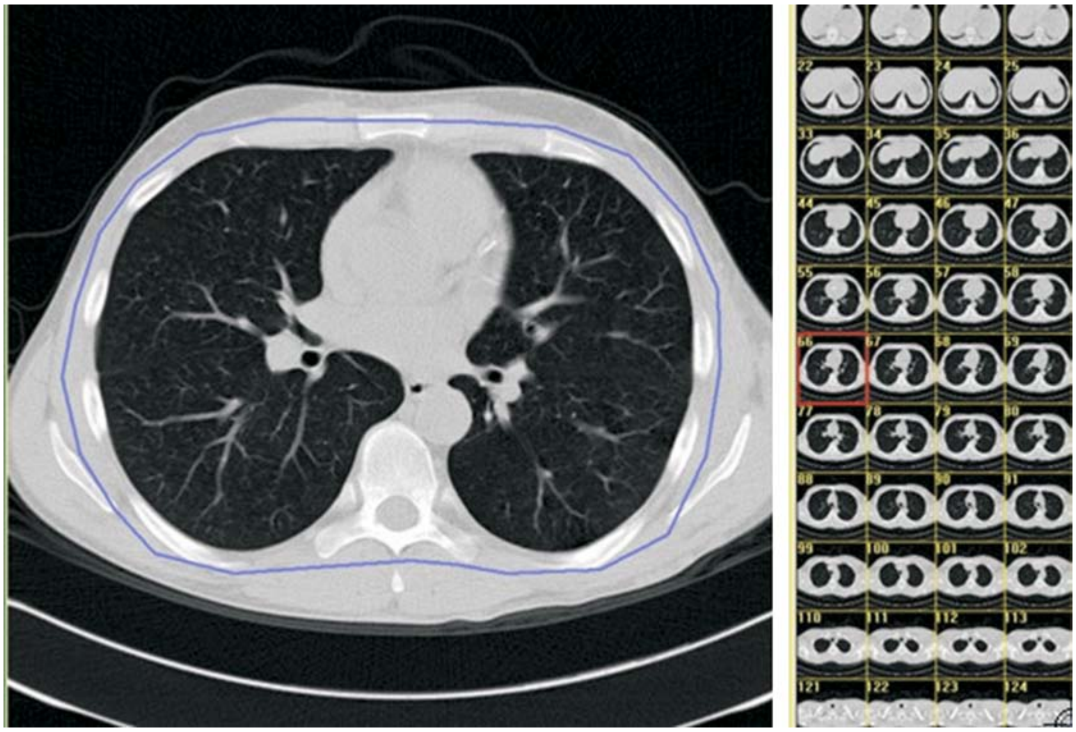

Fig. 1. Axial slice of a patient CT. The blue line represents the outer boundary of the lung cavity. It is refined in a post process to define the lungs.

The data were collected from images resulting from CT scans collected as part of a medical diagnosis of the subjects' torsos. Care was taken to exclude subjects with evident pathologies that affect lung dimensions such as lung collapse, incomplete volume, and tumors big enough to affect the lung size. Smokers were not excluded from the study.

MATERIALS AND METHODS

Data collection

Torso images were collected from males and females in the course of routine medical diagnostics (25 February 2010 to 21 April 2010). The data were collected on two computed tomography (CT) scanners: a Siemens Somatom Sensation (64 slice) (Siemens Canada, 1550 Appleby Line, Burlington, ON L7L 6X7 Canada) or a Phillips Brilliance iCT (256 slice) (Phillips Healthcare, 3000 Minuteman Rd., Andover, MA 01810-1099 USA). Slice thickness was set to 2.5 mm for all scans. The files were anonymized by CHUM staff prior to sending the data to the HML. The only patient data provided to the HML were gender, age, height, and weight. In some cases not all the data were present (e.g., age).

Data manipulations

The voxel (a volume element representing a value on a regular grid in three dimensional space) lung phantoms were generated as follows. The image sets from CHUM were processed using 3D-Doctor (Able Software Corp., 5 Apple Tree Lane, Lexington, MA 02470) and other tools (Kramer et al. 2010). Fig. 1 shows a typical image with a region of interest (ROI) drawn around the lung cavity. The ROI must be sufficiently large to include the lung cavity in any of the image slices in the set. The lungs were then defined using the interactive segmentation tool in 3D-Doctor. Each DICOM (Digital Imaging and Communications in Medicine) image set had its own range of intensities, so the boundary selection was visually selected

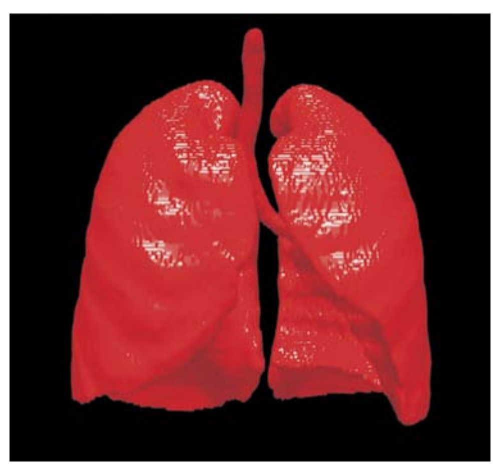

Fig. 2. Rendered lung set used for the linear dimensions and volumes.

Table 1. Characteristics of the patient data set from CHUM.

	Female			Male		
Parameter	Age (a)	Height (cm)	Weight (kg)	Age (a)	Height (cm)	Weight (kg)
Min Value	21.0	145.0	35.8	23.0	157.0	53.0
Max Value	85.0	177.0	111.0	82.0	188.0	159.0
Average	57.7	160.3	67.7	55.7	174.1	83.4
Median	59.0	160.0	66.0	55.0	175.0	83.7
Mode	61.0	170.0	54.4	60.0	170.0	80.0
StDev	14.1	7.4	14.7	12.1	7.2	18.3

by the operator. It varied from image set to image set and was obtained by selecting the appropriate pixel density that corresponded to the outer edge of the lung. Once that process was completed, each slice was manually inspected and adjusted if required to make sure that the segmentation was correct. Once completed, the lungs were rendered (see Fig. 2) into a 3D object (voxel lung phantom) that could be manipulated onscreen.

Five linear dimensions were measured using tools in 3D-Doctor on each lung set so created: peak-to-peak, which is the distance between the apexes of the left and right lung; height, which is measured from the apex of each lung to the center of the lung base; maximum height, which is the distance from the apex of each lung to the lowest part of that lung; width, which is the maximum width of the lung; and depth, which is the maximum depth of the lung. Height, maximum height, width, and depth were measured for left and right lungs. In addition to the linear dimensions, the volumes of the left and right lung, and of both together, were measured. Lung volume was estimated simply by counting the number of voxels in the left and/or right lung and multiplying by the volume of the voxel.

Software

3D-Doctor v4.0 was used to create boundary files and for simple changes to a structure. Rhinoceros v4.0 (McNeel and Associates, 3670 Woodland Park Ave. N, Seattle, WA 98103) was used to edit the three dimensional shapes created by 3D-Doctor. Microsoft Excel was also used for data manipulations and simple curve fitting.

RESULTS AND DISCUSSION

Data Set

The data consisted of 85 females and 81 males. The characteristics of the data set are shown in Table 1. While age was present on each data file, the female set was missing 18 height and 10 weight measurements. Similarly the male data set was missing 35 height and 24 weight measurements. These incomplete data were not used when calculating the empirical relationships discussed below.

Data were collected from CT scans, which have the patient supine, the same position as for whole body counting; however, lung counting is performed with the subject reclined at about 45 degrees to the horizontal. While the change in position could make a small change to the lung shape (i.e., flatten it somewhat), this is mitigated by the lung inflation that is part of the CT scan procedure.

The results of measuring the linear dimensions are summarized for males and females in Figs. 3 and 4 and Table 2. The boxplots can be interpreted as follows. The box shows the center of the distribution. The bottom of the box is drawn at the first quartile and the top at the third

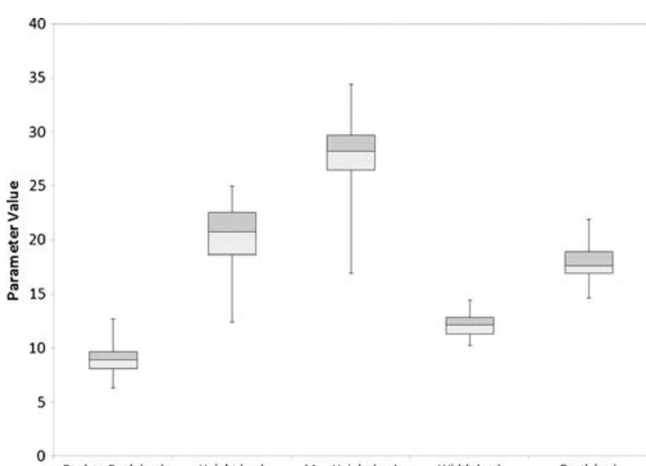

Fig. 3. Boxplot for the measured parameters (peak-to-peak, height, maximum height, width and depth) for the male data set.

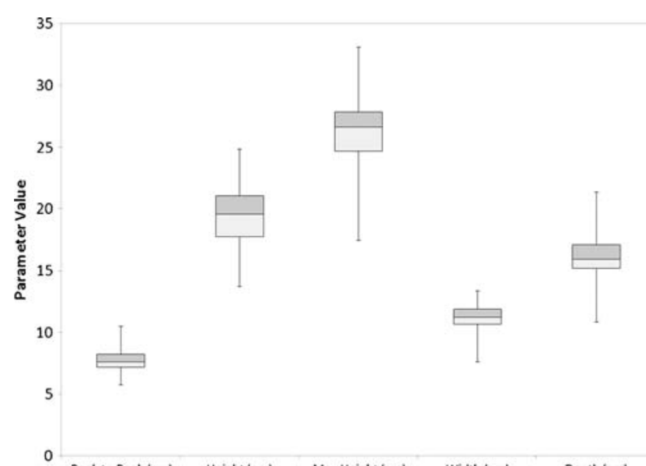

Fig. 4. Boxplot for the measured parameters (peak-to-peak, height, maximum height, width and depth) for the female data set.

Table 2. Summary of linear dimensions and lung volume for the male and female data sets listing the mean value, standard deviation and the median, which is in parentheses, for each data set.

	Lung	Male	Female	Combined
Peak-to-peak		8.9 ± 1.1 (8.9)	7.7 ± 0.9 (7.6)	8.3 ± 1.2 (8.2)
Height	Left	21.0 ± 2.1 (21.8)	19.0 ± 2.5 (20.3)	19.8 ± 2.6 (20.0)
	Right	21.0 ± 2.1 (21.3)	19.0 ± 2.5 (19.3)	20.6 ± 2.6 (21.0)
Max. Height	Left	28.2 ± 2.2 (27.4)	26.0 ± 2.7 (25.6)	26.1 ± 2.6 (26.5)
	Right	21.0 ± 2.1 (21.3)	26.0 ± 2.7 (26.3)	26.9 ± 2.7 (26.9)
Width	Left	12.3 ± 1.1 (10.6)	11.1 ± 1.0 (9.7)	10.0 ± 1.0 (10.0)
	Right	12.3 ± 1.1 (12.3)	11.1 ± 1.0 (11.2)	11.6 ± 1.2 (11.4)
Depth	Left	18.0 ± 1.5 (18.4)	16.2 ± 1.7 (16.2)	17.1 ± 2.0 (17.1)
	Right	18.0 ± 1.5 (17.6)	16.2 ± 1.7 (15.9)	16.9 ± 1.8 (17.0)
Volume	Left	2738 ± 533 (2817)	1968 ± 505 (2028)	2301 ± 636 (2262)
	Right	3121 ± 605 (3226)	2300 ± 547 (2332)	2663 ± 667 (2583)
	Total	5858 ± 1094 (5882)	4268 ± 1028 (4351)	

Dimensions are in cm except for the volume, which is measured in cm^3.

quartile. The median value is the solid line drawn across the box, and the lines extending from the box are known as whiskers; they indicate the upper and lower range of the data that lie outside the box. They are not confidence limits.

As mentioned above, the patients had taken a deep breath prior to the imaging so that their lungs were larger than the at-rest volume, although not fully inflated; therefore, the data represent larger lungs than for subjects at rest.

Lungs, when they inflate, change mostly in the longitudinal direction (height) with a smaller increase in the sagittal and anteroposterior directions, so the most affected linear dimension is "height." The change in an "at-rest volume" and a "deep breath volume" is likely to be the ratio of the tidal volume to the functional residual volume. Using typical values (ICRP 1994), this change is about 20%. This may seem large, but it has to be apportioned over the linear dimensions as they are "cubed" to determine volume. If the lung is assumed to be an ellipsoid, a 20% change in volume for a typical value in this data set results in a 2.5–5% change in the sagittal and anteroposterior diameters and a 10–15% change in "height."

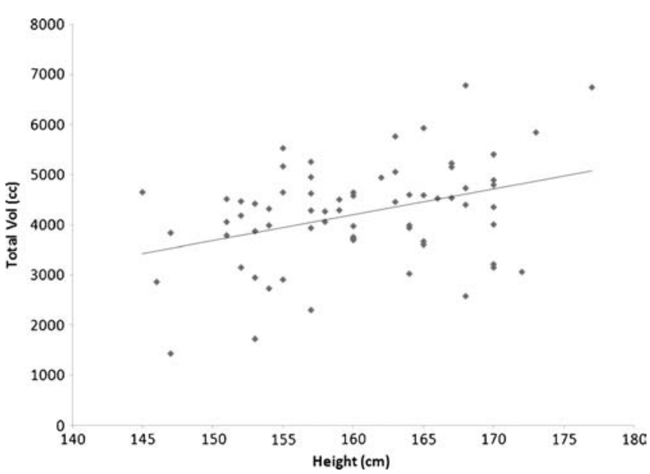

Fig. 5. Plot of total lung volume for females as a function of height (m).

Empirical relationships

The data were treated in a variety of ways to determine if there was an empirical relationship between any of the linear dimensions and lung volume with weight, height, age, and size measured as $\sqrt{(\text{weight}/\text{height})}$.

One of the better plots is shown in Fig. 5, which shows the total lung volume for females as a function of height. Linear regression of this fit gives a gradient of 51.6 ± 15.9 and intercept of –4,051 ± 2,550. The correlation coefficient is 0.139 and the standard error for the y-estimate is 952. Plots for the left and right lungs give similar data. Analyzing the total lung volume as a function of height, weight, and age gives slightly better values. For females, the correlation coefficient is 0.15, the standard error on the estimate of y is 959.4, the F statistic is 3.8, and the error on the parameters is large: age (835%), height (31%), weight (98%), intercept (54%). The male data set is slightly smaller but has a similar fit. The correlation coefficient is 0.19; the standard error on the estimate of y is 1,041.9; the F statistic is 3.2; and the error on the parameters is large: age (110%), height (35%), weight (198%), intercept (77%).

The data show that the linear parameters are almost independent of an individual's weight or height for both the male and female data sets. The same trend (or lack thereof) is observed for any of the linear parameters as a function of the size parameter or age. For example, a linear regression performed on the female lung depth as a function of age, height, and weight gave a regression with

Table 3. Empirical relationships given in ICRP 66 (ICRP 1994).

Parameter	Gender	Equation	RSD
Total Lung Capacity	Male	$7.99 \cdot H - 7.08$	0.70
	Female	$6.60 \cdot H - 5.79$	0.60
Vital Capacity	Male	$5.76 \cdot H - 0.0263 \cdot A - 4.34$	0.56
	Female	$4.43 \cdot H - 0.026 \cdot A - 2.89$	0.43
Functional Residual Capacity	Male	$2.34 \cdot H + 0.009 \cdot A - 1.09$	0.60
	Female	$2.24 \cdot H + 0.001 \cdot A - 1.00$	0.50
Total Lung Capacity (this work)	Male	$6.33 \cdot H - 5.08$	1.03
	Female	$5.16 \cdot H - 4.05$	0.96

H = height in meters, A = age in years, RSD = residual standard deviation.

a correlation coefficient of 0.11 and a standard error on the estimate of Y of 1.6. The uncertainties on the fitting parameters were, expressed as a percentage, age (53%), height (217%), weight (57%), and intercept (52%).

Comparison with existing relationships

Other work has found that total lung volume is correlated with the cube of the height (Hepper et al. 1960; Cook and Hamman 1961); however, this was not found in this work. The CT images were taken as part of a medical diagnosis, and the people involved were not being measured for total lung volume. Despite being asked to take a deep breath prior to imaging, there was likely a large variance in the amount of full inflation, if any, achieved by the patients, and this has resulted in the lack of correlation of lung volume with the person's height.

The Human Respiratory Tract Model for Radiological Protection (ICRP 1994) gives several empirical relationships for the calculation of lung volume. Table 3 gives empirical equations for the Total Lung Capacity (TLC), the Vital Capacity (VC), and the Functional Residual Capacity (FRC). It is interesting to note that the weight of the individual is not a significant factor, in agreement with this work.

The subjects included in this work were asked to take a deep breath before the CT image set was obtained; however, this was not representative of a fully inflated lung. The lung volume measured from the 3D images reconstructed from the DICOM set is closest to the TLC. The VC includes the anatomical dead space that is part of the 3D image, and the FRC represents an exhaled lung.

The linear regression on TLC for data in this work is also shown in Table 3. The relative standard deviation (RSD) values of this work's data are higher than the ICRP's equation, indicating higher variability in the data set; however, this is to be expected as the work cited in ICRP 66 (Quanjer 1983) showed that the lung volumes were measured under very controlled conditions.

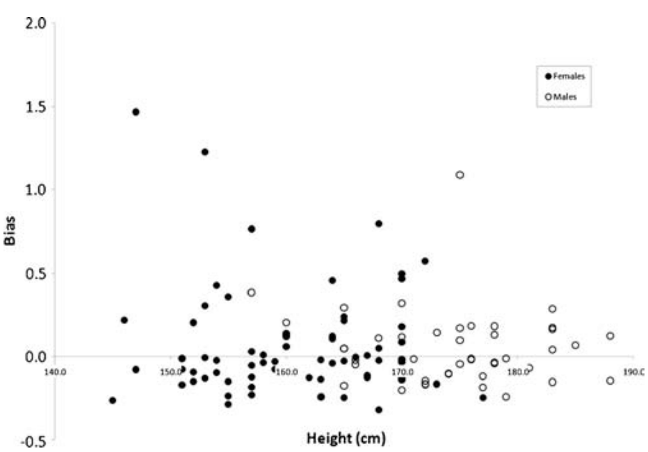

Fig. 6. Agreement of the predicted lung volumes with the measured lung volumes expressed as bias values as a function of height (m) for the males and females in this work.

Using the equations developed in this work to back-calculate the lung volumes and then expressing them as a bias, (predicted-measured)/measured, gives agreement between −24% to 109% for the male data set and −32% to 147% for the female data set. These data are shown in Fig. 6, which shows that the predictive power of these equations predicts most values to within 50% of the true values, but a few are less accurate—being from 50% to 150% of the true value. The extreme values may be due to patients who did not take a "deep" breath prior to the CT examination, as the measured lung volumes are much less than the predicted values.

CONCLUSION

This work has shown that a large amount of data exists in the medical community that can be of value to the health physics community. Recall, the intent of this study was to: 1) determine the range of linear dimensional parameters that could be used for torso phantom development for males and females; 2) understand and characterize the variability of linear lung dimensions for males and females; 3) replace the brief table in ICRP 23 with more modern data for males and females; 4) identify an empirical formula that would predict linear dimensions of human lungs from age, height and/or weight for males and females; 5) characterize the left, right, and total lung volumes of males and females in this data set; and 6) compare the lung volumes of males and females to published equations for determining lung volumes.

This work has found that individual linear dimensions of lungs are essentially independent of age, height, and weight, so predictive equations cannot be formulated; however, the ranges of those parameters have now been established for the population studied herein. The data presented here is more modern than the brief table that appeared in ICRP 23, and the average values could be used as future guidelines. Whole lung volumes have been determined from the voxel lung phantoms, and empirical formulae have been developed for males and females in this data set—and they compare favorably with the published values in ICRP 66. That being said, the predictive power of these equations is not high.

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