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Chest Wall Thickness measurements and the dosimetric implications for male workers in the Uranium Industry.

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INTRODUCTION

Chest wall thickness (CWT) is often estimated by biometric equations; however, as Vickers (1) has shown, these equations are site specific. Large errors can be introduced into the CWT estimate, and hence the activity estimate, if a literature equation is simply applied to a worker population without verification. Health Canada's Human Monitoring Laboratory (HML), which operates the National Calibration Reference Centre for *In Vivo* Monitoring (2), has measured chest wall thicknesses (CWT) of a representative number of male workers at Canadian uranium refinery, a conversion plant, and a fuel fabrication site to derive the appropriate biometric equation. Estimates of the adipose content of the chest wall was made on a selected group as the adipose mass fraction (AMF) can have a significant effect on the transmission of low energy photons (3).

The CWT data has been used to estimate the sensitivity of lung counting for natural uranium for a phoswich and germanium based lung counting system. The dosimetric implications have been put into the perspective that will result from the imminent change to the Canadian Regulations. This change will result in a dose limit to 100 mSv in a five-year period with a maximum of 50 mSv in any one year. An average of 20 mSv per year has been assumed in this paper.

METHODS AND MATERIALS

Ultrasound Measurements: The HML's portable ultrasound unit (Aloka SSD-500 echo camera) used a 5 MHz linear array to make the measurements. Each subject was asked to strip to the waist. A clear template and a black marker were used to mark 11 measurement positions on the subject's chest above each lung. These positions represented areas of the chest that would be measured by both germanium and phoswich detectors. The ultrasound probe was covered with Aquasonic 100 gel prior to application to the subject's chest. The gel was reapplied to the probe whenever signal loss prevented a clear image being obtained on the ultrasound unit.

An estimate of the AMF was also made from selected ultrasound images taken at the conversion facility and at the refinery by measuring the thicknesses of the fat and the muscle layers in the imaged chest wall using the instruments internal calipers. Estimates of the AMF were also made at each measurement point on the subjects measured at the fuel fabrication site.

Eighty five male subjects at a uranium conversion facility were measured in a sitting geometry simulating the position of a germanium lung counter. Thirty-five male subjects were measured at a uranium refinery and eleven male subjects were measured at a fuel fabrication plant. The latter two groups were measured in a sitting and a supine position. The supine position simulates the counting position in the phoswich based lung counting system used by the company.

Demographic Data: The subject's badge number, height, weight, age, and work location were recorded. The height, weight, and age data were used to determine an empirical equation that can be used to calculate chest wall thickness for routine counting. Ultrasound measurements would be used in the event of an actual contamination.

Counter Calibrations: The LLNL torso phantom (4) containing 701 mg of natural uranium homogeneously distributed throughout the lung substitute material was used to estimate the counting efficiency of both the phoswich and the Ge lung counting systems. The phantom was counted with and without the C-series overlay plates to simulate 100% muscle and thereby give counting efficiency as a function of muscle-equivalent-chest wall thickness directly.

Phoswich Lung Counter: The phoswich lung counter consists of a low background monitoring chamber, a phoswich detector assembly and multichannel analyzer, all enclosed in a 12.2 meter air conditioned transport trailer. The counting chamber is constructed of 10.2 cm thick selected low background steel with a 3 mm lead liner. The interior dimensions are: 213 cm long, 132 cm high and 76 cm deep. Subjects are counted in a supine position using detectors positioned both above and below the chest cavity.

The lung counter consists of four phoswich detectors. Each detector consists of a NaI(Tl) crystal (12.5 cm diameter; 1.25 cm thick) optically coupled to a CsI(Na) crystal (12.5 cm diameter; 5.1 cm thick optically coupled to a photomultiplier tube. The phoswich detectors are connected through a multiplexer to a microcomputer based multichannel analyzer. The multichannel analyzer functions are controlled by the microcomputer, which also performs the data analysis and storage. Data were analyzed for the front two-detector arrays only.

Germanium lung counter: The HML's germanium lung counting system consists of four large area germanium detectors supplied by EG&G Ortec. Each detector, which is cooled by a 17 liter Dewar, is 70 mm in diameter and 30 mm thick. The beryllium entrance window is 0.5 mm thick. The detectors are housed in a counting chamber that is constructed of 20 cm thick low background steel. The shield's interior is covered with a lead liner that is approximately 0.6 cm thick. Spectra acquired from the individual Ge detectors were summed and analyzed as an array.

Background Measurements: The background count used for the MDA estimate of the Ge lung counter was obtained from the spectrum of an uncontaminated person who was measured for 1800 seconds in the HML's lung counter. The counts in the appropriate spectral region of interest were used with the appropriate calibration factor for that energy. Units of MDA will depend on the units of the calibration factor and the counting time. For natural uranium, the HML uses both Bq and milligrams. The following formula is based on the work of Currie (5), with Brodsky's (6) modification:

$$MDA = \frac{4.65\sqrt{N}}{ET} + \frac{3}{ET}$$

Where: N = background counts in the region of interest, E = counting efficiency (cps Bq^{-1} or cps mg^{-1}), T = counting time (sec).

Similarly, the background count used for the MDA estimate of the phoswich lung counter was obtained by measuring an uncontaminated person for 1800 seconds who was of comparable size to the average worker. It is recognised that background, especially in a phoswich lung counter, varies with the individual's size; however, to build in a size dependent background is beyond the scope of this work. It is suggested that readers applying this methodology measure a range of physical types to characterise their counting systems.

RESULTS AND DISCUSSION

Ultrasound Measurements: Comparison of the data collected in the germanium detector counting regions with that of the phoswich region showed no difference in the mean chest wall thickness: a t-test showed that the null hypothesis (no difference between means) was accepted. Results of the t-test for each site were 0.0014, 4.1 $x10^{-5}$, and 0.027. Each site was then compared using ANOVA. The F value was 0.68 which is less than the value of $F(2,133)$ indicating that the null hypothesis is accepted. The data has, therefore, been kept as a single set. The eleven measurement points on both left and right lungs were averaged to give an average chest wall thickness above each lung. The twenty two points were also combined and averaged to give an average chest wall thickness for a lung counting detector array - this data are reported in this paper.

Table 1 shows mean CWT, standard deviation of the mean, standard deviation of a single measurement of the CWT, the median CWT, minimum CWT and maximum CWT measured at the uranium refinery, conversion plant, and fuel fabrication sites for seated and supine subjects. The grand average of a male supine subject was 3.73 cm. The supine posture used in the facility's lung counter increased the average CWT by about 0.3 cm to 0.5 cm. This observation agrees with earlier work (7) and shows that there will be a decrease in counting efficiency compared to a seated geometry; consequently, there will be an increase in the minimum detectable activity (MDA).

The AMF of the chest wall of conversion plant and refinery workers lies in the range 5% to 40% with a mean of 22%. The fuel fabrication workers had a mean AMF of 21 ± 6%. The range of the mean AMF was 17% to 28%, but individual measurement points on the workers' chest were found to vary from 4% to 42%. This data seems comparable to the literature data - see Table 2. Comparison of the data in Table 1 with other literature data (1,7,8) indicate that the uranium refinery, conversion plant, and fuel fabrication workers have larger CWT values. Unfortunately this can not be statistically tested as there are insufficient literature data to make the comparison.

Biometric Equation: Table 3 summarises the weight, height and age data that were used to derive an empirical equation to predict CWT. The largest CWT of 8.29 cm has been excluded from this analysis as the height and weight data were not available for this individual. Linear regression was performed on the data using the function published elsewhere (8) and shown below:

$$CWT = a + b\left(\frac{Wt}{Ht^2}\right) + c(age)$$

Where: **CWT** is measured chest wall thickness (cm), **Wt** is subject weight (kg), **Ht** is subject height (m), and **a**, **b**, and **c** are the coefficients of regression.

The results of the regression are shown in Table 4. The standard error in Table 4 indicates that 68% of the predicted CWT values will be within 0.5 cm, 95% within 1 cm, and 99% within 1.5 cm. This supports the rationale that the biometric equation be only used for routine counting and that ultrasound measurements be used to determine an accurate CWT in case of a positive lung burden being discovered.

Counter Calibrations: The results of the lung counter calibrations are shown in Table 5. The thicker values (4.73 cm and above) were obtained by stacking plates C1 - C3 on the C4 plate when the phantom was measured with the phoswich lung counter. This is recognised as an unsatisfactory method but is probably equally as effective as extrapolating the efficiency curves obtained with the Ge lung counting system using multiple regression; however, in view of the chest wall thickness results measured at the facilities, it seemed necessary to make the attempt to investigate the efficiency (and hence MDA values) at the larger thickness values. Nevertheless, values above 4.2 cm should be treated with reservation.

The astute reader will notice that the efficiency values for the 63 keV photons measured by the phoswich counting system do not fall off as fast as the 185 keV photons. The converse would be expected as the 63 keV photons are more highly attenuated than the 185 keV photons. However, in phoswich counting, regions of interest are predefined for the nuclide of interest and the efficiency is measured in terms of gross counts. Therefore, all counts falling in that region are assumed to be from the radionuclide of interest (in other words no peak fitting is performed). The efficiency of the 63 keV photons does not fall off as quickly as expected because as the CWT increases the higher energy peaks (93, 140, 185 keV) scatter more photons down into the lower energy region. This results in the gross counts in the 63 keV region decreasing slower than the counts in the 185 keV region. This apparent discrepancy is compensated by the assumption that the phantom is expected to scatter photons the same way as a person of that CWT would, so the counting efficiency is valid when comparing the phantom's calibration data to that of a person.

Implications for MDA - Germanium counting: Table 6 shows calculated MDA values for the four-detector germanium array. Given that the range of CWT values is 1.9 cm to about 8 cm, the achievable range of MDA's is about 8 mg to 57 mg of natural uranium using photons emitted from ^{235}U (although a slight improvement can be obtained by measuring the photons emitted from ^{234}Th, they cannot be used for reasons given below). The grand average CWT is 3.7 cm so the corresponding MDA will be about 14 mg. Doubling the counting time to 60 minutes will reduce the MDA to about 10 mg of natural uranium.

Although the higher energy (185 keV) photons of ^{235}U are less attenuated than the 63 keV photons from ^{234}Th, the combination of the low natural abundance (0.712%), branching ratio (54%), and decreased counting efficiency as a function of CWT interact to slightly increase the MDA, relative to ^{234}Th.

Implications for MDA - Phoswich counting: Table 7 gives MDA values for a two-phoswich-detector array. Certain assumptions have been made in obtaining the values in Table 7: count data were obtained for fixed regions of interest, and background correction is performed by matched subject counting. The Table shows that the phoswich detectors used in this study have a lower MDA for natural uranium if it is estimated from the 63 keV photopeak emitted from the daughter product ^{234}Th compared to the MDA values estimated from the 185 keV photons emitted by ^{235}U; however, this assumes that the daughter (24 day half-life) is in equilibrium with the parent ^{238}U. If the equilibrium is not established, then natural uranium must be estimated from the ^{235}U photopeak and the accuracy of this estimate depends on the mass composition of natural uranium. An uncertainty will be introduced into the activity estimate if any enrichment or depletion has occurred during refinement.

Lung counting of uranium refinery, conversion plant, and fuel fabrication workers for natural uranium assumes that daughter equilibrium has not been established. Lung burdens are, therefore, determined from the 185 keV photons emitted by ^{235}U. Comparing the values in Tables 5 and 6 one sees that the two-detector-phoswich array is more sensitive than the germanium detector array. For example, at a muscle-equivalent-chest-wall-thickness of 4 cm the phoswich array's MDA (^{235}U) is approximately 12 mg whereas the germanium array's MDA (^{235}U) is about 15 mg.

Dosimetric implications: Table 8 shows the expected lung burden at various times following an intake of either 428 mg or 128 mg (the Annual Limit on Intake for Type M and S, i.e., that amount of activity that will give a committed effective dose of 20 mSv). The values were calculated from data published elsewhere (9). Type F was not considered as it will not be retained in the lung and should be part of a urinalysis bioassay program.

Four intake scenarios were investigated: one day before a lung count, seven days before a lung count, six months before a lung count, and one that occurred just after the last lung count, assuming an annual frequency. Consider a hypothetical individual who has a CWT equal to the average value (3.7 cm, AMF 30%) has an intake in each time scenario. The hypothetical individual is measured using a phoswich array lung counter and the activity estimate is based on ^{235}U. Type M intake: it will be readily detected on days 1 and 7; however, as the MDA for a 30 minute count time is 10.8 mg, days 180 and 360 will be missed. If the counting time is increased to 60 minutes the MDA would be expected to drop to 7.7 mg, and day 180 will be detected, but not day 360. Type S intake: days

1 and 7 may be detected if the counting time is 60 minutes, but days 180 and 365 will be missed as they are well below the MDA.

The conclusions are not substantially different if the counting system is a germanium lung counter; however, there are some modifying factors. The CWT of a seated subject is less than that of a supine subject: the average decrease in the CWT for the workforce was 0.3 cm. This decrease in the CWT will lower the MDA slightly but not sufficient to make any substantial difference in the level of detection and the conclusions presented below. The hypothetical individual is now measured using a germanium array lung counter and the activity estimate is based on ^{235}U. Type M: days 1, and 7 would be detected, but not days 180 and 360 - there is no change in this finding even if the counting time is increased to 60 minutes. Type S: days 1, 7, 180 and 365 will be missed as they are below the MDA. Similarly, there is no change if the counting time is increased to 60 minutes.

For countries using earlier ICRP recommendations and a dose limit of 50 mSv/y the situation is somewhat different. The values in Table 8 would be multiplied by 2.5 and then compared against the MDA values in tables 6 and 7. Under these circumstances the hypothetical individual would have a Type M or S intake detected by a phoswich lung counter or a Ge lung counter for days 1, 7, 180 and 360 if the counting time was 60 minutes.

CONCLUSIONS

The average chest wall thickness of the seated persons measured at the uranium conversion plant, refinery, and at the fuel fabrication facility was 3.7 cm. Persons measured in a seated geometry had a thinner chest wall thickness than persons measured in a supine geometry - the average decrease was 0.3 cm. It follows that a seated geometry will give a slightly lower MDA (or decision level) than a supine geometry.

Achievable MDA's (30 minute counting time) with a two-phoswich-detector array lie in the range of 6.7 mg to 19.1 mg of natural uranium based on the ^{235}U emissions over a range of CWT of 1.6 cm to 6.0 cm. The average achievable MDA is about 11 mg which can be reduced to about 8 mg by doubling the counting time. Similarly, MDA's (30 minute counting time) obtainable with a germanium lung counting system will lie in the range of 7 mg to 30 mg of natural uranium based on the ^{235}U emissions over a range of CWT of 1.6 cm to 6.0 cm. The average achievable MDA will be about 14 mg which can be reduced to about 10 mg by doubling the counting time. Unfortunately, all of these MDA values are close to, or above, the predicted amounts of natural uranium that will remain in the lung after an intake equivalent to the Annual Limit on Intake that corresponds to 20 mSv.

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Table 1: Site specific data showing number of measured participants (N), mean CWT, standard deviation of the mean, standard deviation of a single measurement of the CWT, the median CWT, minimum CWT and maximum CWT measured at the uranium refinery, conversion plant, and fuel fabrication sites for seated and supine subjects.

Site	N	mean CWT (cm)	$stdev_{mean}$ (cm)	stdev (cm)	median CWT (cm)	min CWT (cm)	max CWT (cm)
Conversion Plant (seated)	88	3.75	0.10	0.91	3.80	1.92	8.29
Refinery (seated)	37	3.79	0.12	0.69	3.65	2.59	5.23
Refinery (supine)	35	4.06	0.12	0.71	3.95	2.85	5.58
Fuel Fabrication (seated)	12	3.36	0.15	0.52	3.36	2.22	4.34
Fuel Fabrication (supine)	12	3.81	0.15	0.51	3.91	2.86	4.44
Grand Average (seated)	137	3.73	0.07	0.82	3.68	1.92	8.29

Table 2: Chest wall thickness (CWT) parameters of two cohorts (33 and 135 male subjects) from the literature.

	Mean (cm)	Minimum (cm)	Maximum (cm)	Reference
CWT (cm)	3.20	2.6	4.5	(1)
Relative adiposity	0.34	0.23	0.53	
Weight (kg)	87	61	129	
Height (m)	1.80	1.61	1.93	
Age (y)	43	25	72	
CWT (cm)	2.99	1.9	4.2	(8)
Relative adiposity	0.25	0.16	0.36	
Weight (kg)	74	50	116	
Height (m)	1.73	1.52	1.96	
Age (y)	45	20	63	

Table 3: Site specific data for weight, height and age of the participants at the uranium refinery, conversion plant, and fuel fabrication sites

	Weight (kg)			Height (m)			Age (y)		
Site	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
Conversion Plant	91.6	150.0	63.5	1.79	1.90	1.60	45	59	23
Refinery	86.3	109.3	65.3	1.76	1.91	1.55	43	63	30
Fuel Fabrication	84.1	95.5	65.6	1.74	1.83	1.64	47	61	29

Table 4: Parameters for the fitted regression line for CWT as a function of subject weight, height and age for the combined data set (uranium refinery, conversion plant, and fuel fabrication sites).

Parameter	Value	Standard Deviation
a (cm)	0.384	0.351
b (cm m^2 kg^{-1})	0.146	0.010
c (cm y^{-1})	-0.017	0.005
Corr coeff	0.782	
Stand. Error (cm)	0.458	

Table 5: Counting efficiency (cps/photon) data of the LLNL torso phantom for either a two-phoswich detector or a four-detector Ge lung counting array measuring natural uranium in the lung as a function of muscle-equivalent-chest-wall-thickness (MEQ-CWT).

	Phoswich			Germanium	
MEQ-CWT (cm)	From ^{234}Th (63 keV)	From ^{235}U (185 keV)	MEQ-CWT (cm)	From ^{234}Th (63 keV)	From ^{235}U (185 keV)
1.63	0.3046	0.1172	1.54	0.0185	0.0170
2.29	0.2755	0.1000	2.19	0.0139	0.0134
2.91	0.2496	0.0870	2.80	0.0109	0.0109
3.45	0.2262	0.0753	3.35	0.00906	0.00942
4.19	0.1933	0.0623	3.99	0.00689	0.00752
4.73	0.1778	0.0551	4.00	0.00687*	0.00749*
5.48	0.1556	0.0459	5.00	0.00462*	0.00539*
6.01	0.1415	0.0410	6.00	0.00311*	0.00388*

* Extrapolated values

Table 6: MDA values for a four-detector Ge array using a 30 and 60 minute counting time using background counts for an uncontaminated individual and the efficiency data from Table 5.

	MDA $_{(T=30\ min)}$ - nat U (mg)		MDA $_{(T=60\ min)}$ - nat U (mg)	
MEQ-CWT (cm)	From ^{234}Th (63 keV)	From ^{235}U (185 keV)	From ^{234}Th (63 keV)	From ^{235}U (185 keV)
1.54	5.0	6.8	3.6	4.8
2.19	6.7	8.6	4.7	6.1
2.80	8.5	10.5	6.0	7.4
3.35	10.3	12.2	7.3	8.6
3.99	13.5	15.3	9.5	10.8
4.00*	13.5	15.3	9.6	10.8
5.00*	20.1	21.3	14.2	15.1
6.00*	29.9	29.6	21.1	20.9

* Extrapolated values

Table 7: MDA values for a two-detector Phoswich array using a 30 and 60 minute counting time using background counts for an uncontaminated individual and the efficiency data from Table 5.

MEQ-CWT (cm)	MDA $_{T=30\ min}$ - nat U (mg)		MDA $_{T=60\ min}$ - nat U (mg)	
	From ^{234}Th (63 keV)	From ^{235}U (185 keV)	From ^{234}Th (63 keV)	From ^{235}U (185 keV)
1.63	2.1	6.7	1.5	4.7
2.29	2.4	7.8	1.7	5.5
2.91	2.6	9.0	1.8	6.4
3.45	2.9	10.4	2.0	7.4
4.19	3.4	12.6	2.4	8.9
4.73	3.6	14.2	2.6	10.1
5.48	4.2	17.1	2.9	12.1
6.01	4.6	19.1	3.2	13.5

Table 8: Amount of natural uranium retained (mg) in the lung following an acute intake of an amount equal to one Annual Limit on Intake (ICRP 1997).

Day since intake	Amount retained in the lungs (mg)	
	M: (428 mg)	S: (128 mg)
1	24.8	8.2
7	23.1	7.8
180	9.4	4.9
360	5.1	4.1