J.Korean Asso. Radiat. Prot.
Vol.25 No.1 : 3-9(2000)

■論 文■

Chest Wall Thickness Measurement of the LLNL Phantom for Ge Detectors

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Ge 검출기를위한 LLNL 팬텀의가슴벽두께측정

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(1999년 12월 3일 접수, 2000년 6월 21일 채택)

Abstract - The Korea Atomic Energy Research Institute acquired the Lawrence Livermore National Laboratory phantom for calibration of germanium detectors used for in vivo measurement of radionuclides deposited in human lungs. The manufacturer inscribed concentric circles as a phoswich detector positioning guides on the phantom' s torso plate and its overlay plates, and provided the effective thickness of the chest wall for each plate measured at locations over the circles. However, since the germanium detectors are of different sizes, the areas considered for phoswich detectors were no longer applicable for the locations of the germanium detectors on the phantom. Therefore, we re-evaluated the effective thickness of the phantom to determine if the manufacturer's data are valid for germanium detectors in use for in vivo lung counting or if new values must be implemented. Differences no more than 3% in effective thickness were found between the germanium detector regions to be used at the Korea Atomic Energy Research Institute and the phoswich detector regions prescribed by the manufacturer.
Key Words : phantom, calibration, germanium detectors, in vivo measurement, effective thickness, chest wall

요약 - 한국원자력연구소에서는 사람의 폐에 침착된 방사성핵종의 *in vivo* 측정을 위해 사용되고 있는 Ge 검출기의 교정을 위해 LLNL 팬텀을 구입하였다. 제작사는 팬텀 위에서 phoswich 검출기의 위치설정을 돕기 위해 팬텀의 몸통덮개판과 이의 오버레이판 위에 동심원을 그려 놓았으며, 그리고 동심원내에서 측정된 팬텀의 가슴벽유효두께를 제공하였다. 그러나 Ge 검출기의 면적이 phoswich 검출기보다 작기때문에 phoswich 검출기를 위한 동심원은 한국원자력연구소에서 사용중인 Ge 검출기에는 적합하지 않는 것으로 나타났다. 따라서 본 연구에서는 제작사에 의해 제공된 팬텀의 가슴벽유효두께가 Ge 검출기에 적합한지, 새로운 자료가 교정에 사용되어야 하는지를 결정하기 위해 팬텀의 가슴벽유효두께를 재평가하였다. 그결과 한국원자력연구소에서 새로 설정한 Ge 검출기영역과 phoswich 검출기영역에서의 가슴벽유효두께는 다소 차이가 있는 것으로 나타났다.
중심어 : 팬텀, 교정, Ge 검출기, *in vivo*측정, 유효두께, 가슴벽

INTRODUCTION

The lung counting system at Korea Atomic Energy Research Institute(KAERI) consists of two ACT-II units. Each unit consists of two Low Energy Germanium(LEGe) detectors cooled by one Dewar. Each detector is 50.5 mm in diameter and 20 mm thick. The beryllium window is 0.5 mm thick. The ACT-II units are also fitted with a background reduction device which is a graded shield consisting of 1.0 cm of

lead and 0.32 cm of copper. The shield surrounds each two-detector unit.
The lung counting system at KAERI is calibrated using a LLNL phantom[1] supplied by Radiology Support Devices. The phantom consists of a torso, a torso plate and overlay plates that simulate different thicknesses

Figure Captions

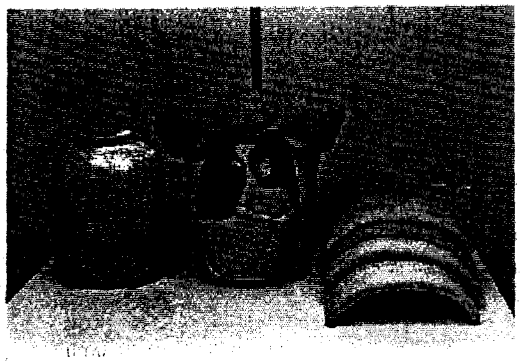

Fig. 1. The LLNL phantom with torso plate and overlay plates.

The overlay plates(B series), when combined with the torso plate, allow the user to simulate different chest wall thicknesses over the lungs of the phantom. The ability to simulate this parameter is important as it affects the counting efficiency, especially at low photon energies. An important consideration in the use of this phantom is the effective thickness of material representing the chest wall for both torso plate and overlay plates. So, the manufacturer inscribed concentric circles as a detector positioning guides on torso plate and all overlay plates, and provided the data on the effective thickness of the chest wall for each plate. However, these circles and the effective thicknesses supplied by manufacturer were suggested for the use of the phoswich detector.
The Human Monitoring Laboratory(HML), which operates the Canadian National Calibration Reference Centre for *In Vivo* Monitoring[2], has previously shown that the manufacturer's values for chest wall thickness of the LLNL phantom are not valid for large area germanium arrays[3]. The LLNL phantom at KAERI is of a slightly different size to the LLNL phantom described in the report by Kramer and Hauck[3] and has different chest wall thickness values. The lung counting system at KAERI consists of smaller diameter germanium detectors than those(70 mm dia. x 30 mm thick) of the HML and are, therefore, placed in different locations. This work was conducted to ascertain whether the manufacturer's values could still be applied to small area germanium detectors that are placed inside the manufacturer's measurement area, but only cover about 25% of that area. This paper describes the procedure used to measure the effective thickness and summarizes these results.

MATERIALS AND METHODS

Measurement Area on the Phantom

The measurement area for the LLNL phantom was determined as follows: the phantom was placed on the KAERI's lung counting bed in a supine position. The torso plate was removed and the detectors lowered vertically so that they were just touching the lung surface. The counting position was selected by visually placing them above the lungs. Once the detectors had been positioned, the detectors were raised vertically and torso plate replaced. The detectors were lowered again so that they just contacted the surface, which is the normal counting position. A black marker was used to draw circles around each detector corresponding to the positions of the four germanium detectors: upper right, lower right, upper left and lower left. The centers of the circles were all within the manufacturer's circles that show where phoswich detectors should be placed. These centers were 3 cm above and below the centers of the manufacturer's circles. This procedure was repeated for the phantom with each overlay plate.
To obtain a representative thickness in each area on the LLNL phantom, the manufacturer's grid was used as measurement positions and every other points was measured. The number of measurement points varied from 18 to 23 in each area depending on how many of the manufacturer' s marks fell within the measuring areas.

Measurement Procedure

The measuring device has been described in detail elsewhere[3]. Briefly, the device consisted of a metal bolt fastened to an adjustable jack. The end of the bolt was polished to a flat surface and this functioned as the "anvil" upon which the surface to be measured was rested. The surface area of the *anvil* was big enough(~20 mm^2) to ensure that the material was compressed simply by resting on it. Above the *anvil* was a piston of a micrometer that was graduated from 0.000 to 2.540 cm. The height of the jack was adjusted so that the *anvil* touched the micrometer when it was adjusted to read 0.000 cm. Once the *anvil* had been set, it was necessary to make a zero reading and record the offset. Usually this was a value about ±0.030 cm. During the measurements this zero position was subject to slight change and so it was redetermined after a series of about eight to ten measurements.

The item to be measured, either the torso plate or an overlay plate, was held in a flat position so the surface was normal to the *anvil.* It was found that the angle at which the torso plate, or the overlay plate, was held could greatly affect the measurement, especially near the edges. Great care was exercised to keep the piece visually normal to the measuring device. The micrometer piston was adjusted so that it contacted the surface of the plate and turned until a small resistance was met. This point was denoted by a "clicking" sound given when further turning of the micrometer was attempted. Typically the micrometer was adjusted to three "clicks" . At this point the micrometer scale was read. The micrometer piston was then backed-off and the piece was repositioned over another sampling point and the process was repeated until all the points within the counting circle were measured.

During the measurement process it was observed that the material was slightly compressed by the micrometer. The compression was quantized by measuring ten locations in the detector circles by two methods: first, the micrometer was adjusted in the usual way (i.e., adjusted until three clicks were heard) and the measurement recorded; second, the micrometer was carefully adjusted until the piston just contacted the surface. The latter measurement was verified using a light to ensure that there was no gap between the surface of the plate and the micrometer, and that there was no visual compression of the surface. In other words, the micrometer was lowered so that it just contacted the surface with no or minimal compression of the material. The error on a measurement due to compression uncertainty and zero adjust is approximately 1%(at one sigma).

Effective Thickness

The effective thickness has been used in the past to compensate for the photon attenuation of the chest wall[4,5,6]. The chest wall thickness of the LLNL phantom is given by the manufacturer as effective thickness values. The effective thickness of each area underneath the detector is calculated as follows:

$$\text{Effective Thickness} = -\frac{1}{\mu_L}\ln\left[\sum_{i=1}^{i=N}\frac{e^{-\mu_L X_i}}{N}\right] \quad (1)$$

where μ_L is the linear attenuation coefficient(cm^{-1}), X_i is the physical thickness measurement(cm) and N is the number of sampling points in the area being measured of the torso plate or overlay plates.

It can be seen from the above equation that the effective thickness is energy dependent. The effective thicknesses have been calculated at 17, 60, 200 and 1500 keV. The linear attenuation coefficients for the above energies were calculated from the mass attenuation coefficients contained in ICRU 44[7] for adipose tissue(r= 0.95 g cm^{-3}) and muscle tissue(r = 1.05 g cm^{-3}) according to equation (2). The linear attenuation coefficient for 17 keV was obtained from interpolating the values obtained from ICRU 44.

$$\mu_L = \mu_m \rho \quad (2)$$

where μ_m is mass attenuation coefficient(cm^2 g^{-1}) and ρ is density(g cm^{-3}).

The addition of the B series overlay plates to the LLNL phantom's torso plate alters the adipose-muscle ratio. The manufacturer supplied information with the LLNL phantom's documentation that allows the user to calculate the adipose-muscle ratio. The equation used to calculate the adipose mass fraction for the LLNL phantom is:

$$AMF = \frac{t_{e,OVP} \times AC \times \frac{\rho_{OVP}}{\rho_{TP}}}{t_{e,TP}} \quad (3)$$

where AMF is the adipose mass fraction, $t_{e,OVP}$ is the effective thickness of the overlay plate(cm), AC is the adipose content of the overlay plate, ρ_{OVP} is the overlay plate density(g cm^{-3}), ρ_{TP} is the torso plate density(g cm^{-3}) and $t_{e,TP}$ is the effective thickness of the torso plate(cm). Equation (3) shows that the adipose mass fractions are calculated from the effective thicknesses which are energy dependent because the linear attenuation coefficient changes with photon energy.

RESULT AND DISCUSSION

Table 1 shows the average of physical thickness measurements in each sampling area and the standard deviation of that set of measurements(at one sigma). The averages of the physical measurements of the plates demonstrate significant variance, i.e. the standard deviation for each set of measurements ranges from approximately 3% to 16%. The upper regions of the LLNL phantom's torso plate vary more than the lower regions because the plate thickens near the edges. The thickness of overlay plates vary only slightly from region to region and within each sampling area. The variability in physical chest wall thickness in each sampling area and for a detector array is dominated by the torso plate as Table 1 shows. Table 2 shows the energy dependent effective thickness for a four detector array on the LLNL phantom and the adipose-muscle ratio of the phantom with any given overlay plate. The effective thickness changes as a function of energy; however, differences are small and the adipose mass fraction values for the B series overlay plates do not change with energy. The effective thickness remains essentially constant after the photon energy exceeds 60 keV as Table 2 shows.

Table 3 shows the manufacturer's values and the bias that will occur if these values are used to calculate counting efficiency instead of the measured values from Table 1. It would be interesting to compare the new regions measured at the KAERI to the original regions as measured by the manufacturer. The manufacturer has measured the physical thickness of 47 points uniformly distributed over the 5-inch diameter counting circles. These are converted to transmission values using an eighth order polynomial that relates physical chest wall thickness of beefsteak to transmission values at 17 keV. These derived transmission value are averaged, as described above. The average transmission value is used to back calculate the effective thickness. This technique gives effective thicknesses that are within 0.015 cm of the method described in this paper. Applying a two-sided *t*-test at a 95% confidence level to each pair of corresponding effective thickness values at 17 keV, one finds that the average thicknesses are not well represented by the original values. The differences are summarized in Table 4 for the phantom' s torso plate with and without the overlay plates. Table 4 shows that almost all areas are statistically distinct. This is surprising as the KAERI lung counter has the detectors placed within the measurement area of the torso plate and overlay plate that is characterized by the manufacturer. Presumably, since the measurement regions are different in size and there is a large variability in the chest wall, this means that for any detector that is smaller than the measurement area on the phantom the user must make their own chest wall thickness estimates.

Comparing Table 1 with Table 2 shows that there is little difference between the physical chest wall thickness and the effective thickness (at any energy). The difference for an array between physical and effective thickness is 0.04 cm and 0.01 cm at 17 keV and 60 keV, respectively. Bearing in mind that the standard error of the mean of the thickness measurements, see Table 1, is between 0.04 and 0.06 at 2s, the difference between effective thickness and physical thickness appears insignificant. Furthermore, the use of effective thickness is questionable[8] if scattered photons from a higher energy emitter contribute to the photopeak of interest.

As the LLNL phantom is constructed of tissue substitute material it should be sufficient to compare a subject's physical chest wall thickness, derived from an ultrasound measurement, with a physical chest wall thickness of the phantom. If low energy photons are being measured, then the adipose mass fraction of the subject must be taken into account and either simulated by the phantom or be eliminated by the use of the Muscle Equivalent Chest Wall Thickness (MEQCWT)[9]; however, if the latter approach is taken the user must not forget to convert the chest wall thickness values of A or B series overlay plates otherwise a bias will be introduced into the activity estimate.

CONCLUSION

It is necessary to re-evaluate the chest wall thickness of the LLNL phantom if detectors other than large area phoswich detectors comprise a lung counting system. The chest wall thickness values supplied by the LLNL phantom's manufacturer apply only to detectors whose diameters correspond to the inscribed circles on the phantom. If germanium detector arrays are positioned at different locations on the phantom's torso, the chest wall thickness should be determined at these positions as the thicknesses of the torso plate and overlay plates are not constant. It seems that the effective thickness although rigorously more correct, offers little advantage over using the physical chest wall thickness measurements when one considers the variability in the physical chest wall thicknesses above the lungs of the phantom; however, the adipose mass fraction still needs to be simulated appropriately as low energy photon attenuation is greatly affected by tissue composition.

ACKNOWLEDGEMENTS

The study was carried out under the national long-term project of nuclear energy development funded by the Ministry of Science and Technology

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Table 1. Physical thickness measurements of the LLNL phantom(B series) and their uncertainties for each of the four detector positions and as an array(sum of all data). TP is the torso plate, OVP is an overlay plate for the LLNL phantom. All units are centimeters.

Phantom configuration	Upper right	Lower right	Upper left	Lower left	Array
TP	1.92± 0.24	1.67± 0.10	1.71± 0.28	1.45± 0.08	1.68± 0.25
TP+OVP B1	2.56± 0.25	2.33± 0.11	2.25± 0.29	2.00± 0.09	2.28± 0.26
TP+OVP B2	3.10± 0.25	2.92± 0.11	2.77± 0.29	2.58± 0.09	2.84± 0.26
TP+OVP B3	3.60± 0.25	3.46± 0.12	3.39± 0.28	3.20± 0.09	3.41± 0.26
TP+OVP B4	4.24± 0.25	3.97± 0.10	3.97± 0.28	3.69± 0.09	3.96± 0.26
	Standard error of the mean(1σ)				
TP	0.06	0.02	0.07	0.02	0.03
TP+OVP B1	0.04	0.02	0.05	0.01	0.02
TP+OVP B2	0.04	0.02	0.05	0.01	0.02
TP+OVP B3	0.04	0.02	0.05	0.01	0.02
TP+OVP B4	0.04	0.02	0.05	0.01	0.02

Table 2. Effective thickness for the LLNL phantom(B series) for the four detector array(sum of all data) as a function of photon energy. AM is the adipose-muscle ratio when overlay plate is on the phantom, TP is the torso plate and OVP is an overlay plate. All units are centimeters.

Phantom configuration	AM6	Photon Energy 17 keV	60 keV	200 keV	1500 keV
TP	0:100	1.64	1.67	1.67	1.67
TP+OVP B1	13:87	2.24	2.27	2.27	2.28
TP+OVP B2	20:80	2.80	2.83	2.83	2.84
TP+OVP B3	24:76	3.37	3.40	3.40	3.40
TP+OVP B4	28:72	3.92	3.95	3.95	3.96

Table 3. Manufacturer's values for the LLNL phantom(B series). TP is the torso plate and OVP is an overlay plate. Bias values are for 17 keV photons measured using the thickness values in this table instead of the values from Table 1.

Phantom configuration	Manufacturer's values Right(cm)	Left(cm)	Array(cm)	Bias(%)
TP	1.85± 0.47	1.69± 0.35	1.78± 0.32	-14
TP+OVP B1	2.54± 0.53	2.27± 0.49	2.42± 0.52	-19
TP+OVP B2	3.22± 0.48	2.88± 0.35	3.07± 0.43	-29
TP+OVP B3	3.64± 0.47	3.43± 0.36	3.55± 0.43	-19
TP+OVP B4	4.23± 0.48	3.87± 0.36	4.07± 0.43	-16

Table 4. Results of two-sided *t*-test(α =0.05) comparing the effective thickness(at 17 keV) of the manufacturer's regions(right, left and array) to the right, left and array regions measured at KAERI. Agreement is denoted by O and a difference is denoted by ×.

Phantom configuration	Upper right	Lower right	Upper left	Lower left	Array
TP	O	×	×	×	×
TP+OVP B1	×	O	×	×	×
TP+OVP B2	×	×	×	×	×
TP+OVP B3	×	×	×	×	×
TP+OVP B4	×	O	×	×	×