THE METHODS OF ABSOLUTE CALIBRATION OF EQUIPMENT FOR MEASUREMENTS OF Pb-210, Pu-239 AND Am-241 IN HUMAN BODY

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Abstract

Calibration of detectors designed for in vivo measurements of ^{210}Pb, ^{230}Pu and ^{241}Am in human body was made by means of an anthropomorphous phantom. Absorption of low energy photons (13 - 60 keV) in materials simulating various biological tissues was studied. The calibration coefficients for the fat tissue (Z=5.9) were 3 times as high as those for the muscular one (Z=7.4), when the tissue thickness was 2 cm. In this connection, the distribution and ratio of the said tissues in human body were studied, using a group of 30 men. In calibration phantom measurements , a tissue equivalent materialsimulating the biological tissue with 22% of fat tissue and 78% of muscular one was used. Detectors have been calibrated for measurements in the energy bands: 10-25 keV ^{239} Pu, 30-55 keV, ^{210}Pb, 10-25 keV and 35-70 keV ^{241}Am and tissue absorber thicknesses in the range from 0.5 to4 cm. The effect of such factors as variations in the shape and location of body organs, radiations of isotopes deposited in the skeleton and some others was taken into account.

Introduction

The interpretation of the results of in vivo measurements of the body ^{210}Pb, ^{239}Pu and ^{241}Am depends on the choice of calibration coefficients appropriate to a specific subject. Detectors may be calibrated, using (a) volunteers who take a safe dose of the assayed isotope [1,2], or (b) anthropomorphous pantoms. The dalibration made on volunteers may provide sufficiently realistic coefficient values which allow for both the complex structure of the bone andsoft tissue shield and the actual distribution of inhaled aerosol throughout the lungs.

However, such factors as the availability of volunteers, the choice of isotopes to simulate a given radionuclide as well as the possibility of modelling of nothing more than a particular case of the radionuclide distribution in the lungs limit the scope of this direct method of calibration.

This paper deals with the further development and improvement of the phantom calibration technique which can provide numerical calibration coefficients for the deposited radionuclide distribution of the lungs-liver-skeleton pattern.

Phantom Design and Tissue Equivalent Materials

The basic criteria used in the phantom development were its tissue equivalence in the 10-100 keV radiation band, modelling of different types of radionuclide distribution and simulation of different thicknesses of the tissue absorber in the region of the chest.

The complete phantom assembly consists of component phantoms, of the skull, chest and arms and legs. A natural human skull is used as the skull phantom and hollow polyethylene cylinders simulate the extremities.

The chest phantom assembly comprises a thin (0.2 cm) plexiglass shell, containing a human thoracic skeleton and man-made organs (the lungs and liver). The free space of the shell is filled with the tissue equivalent material. The shell front wall is movable and it is provided with an attachment for setting it at a desired distance from the phantom sternal ribs. The front wall and the phantom base are supplied with portholes for filling the tissue equivalent material and artificial organ replacement.

Phantom Filling Materials

The muscular and fat tissue and the skin are the main constituents of the human tissue covering the thoracic cage. The calculated values of the mass absorption coefficients for these tissues (cm^2/g) at 10-100 keV shown in Table 1 (Columns 2, 3 and 4) suggest that the fat component should betaken into account in the selection of the tissue equivalent material. (The skin, as far as its absorption properties are concerned, may be assumed to be similar to the muscular tissue).

Table 1

Tissue / Energy band	Pectoral muscle	Fat	Skin	Mean tissue shield	Tissue equivalent material
10	5.249	2.406	4.854	4.579	4.520
15	1.633	0.815	1.499	1.356	I.357
20	0.789	0.409	0.722	0.684	0.673
40	0.259	0.217	0.237	0.247	0.243
50	0.221	0.195	0.199	0.212	0.209
60	0.201	0.184	0.181	0.195	0.195
100	0.170	0.161	0.151	0.166	0.163

The experimental testing of the fat and muscular tissues for their absorption properties were carried on the phantom, which was alternately filled with materials simulating each of these tissues. Attenuation curves for the X-ray radiation of ^{239}Pu emitters uniformly distributed throughout the lung model were obtained. The experimental results given in Table 2 are consistent with the data in Table 1 and support our suggestion.

Table 2

Tissue thickness, cm	1	2	3	4
The ratio of photons which passed through the "fat" to those which passed through the "muscles"	1.4	3	6	10

The ratio of the thicknesses of the fat and muscular tissues covering the thoracic cage in the region of the lungs was measured in 18 male corpses and was found to vary from 34/66 to 10/90, the mean value being 22/78.

Table 1 (columns 5 and 6) gives values of the mass absorption coefficients for the experimental mean tissue consisting of 22% fat and 78% muscles and the tissue equivalent sugar and magnesium oxide based material. The electronic densities of this material and the simulated tissue are $3.24 \cdot 10^{23}$ and $3.32 \cdot 10^{23}$ electron/gram, respectively.

The models of organs , i.e. the lungs and liver, were made of the tissue equivalent material to conform to the average size, shape and density of their human prototypes. The model shell was capron. The lung model shell was filled with a cotton fabric soaked in a NaCl solution to reproduce the desired values of $Z=7.4$ and $\rho=0.27$ g/cm^2. The same material was used for filling the liver and chest shells. The experimental coefficients of self-absorption of ^{239}Pu radiation in the lungs and liver were found to be 3.4 and 5.1, respectively.

Measurement of Soft Tissue Thickness

Owing to a considerable attenuation of low-energy X-ray radiation in the tissues, the accuracy of calibration coefficients selected for the measurements in the monitored subject is materially dependent on the precision of measurements of the thicknesses of soft tissues covering the thoracic cage.

To develop techniques for measurement of soft tissue thicknesses, radiograms of tissues in a special saggital plane were made. Previously, the ratio of the average thickness across this section d_δ to the mean thickness of thes soft tissues across the whole area covered by the detector d_s was obtained in corpse measurements.

The equation $d_\delta/d_s = 1.05 \pm 0.12$ holds for this ratio in a wide range of W/H variations of 0.37 - 0.52, where W - weight , kg; H - height, cm.

The subject's posture proved to influence the thickness of the tissue shield in the chest region. The smallest thickness of the soft tissues over the lungs was found in in vivo measurements to be, when arms are raised and placed behind the back of the subject's head. It was shown experimentally that, for this posture,the absorber thickness decreases by 0.48 cm, as compared with a pose with arms at sides, which is consistent with the value of 0.5 cm, given in This posture was accepted as standard in all subsequent measurements.

The measurement data for soft tissue thicknesses in 26 subjects were related to different parameters of the body and approximated by means of functions, such as $d = \varphi(W,H,C,C_1, C_2)$, where C,C_1,C_2 - circumferences of the chest, waist and hips, respectively, cm; W -weight, kg, H - height, cm. These parameters were measured simultaneously with radiograms being taken. The dependence of d on the selected parameters is best approximated by the equation:

$$d = 118\ W/H \cdot k_1 \cdot k_2 - 39.2, \text{ where } k_1 = C/C_2,\ k_2 = C/C_2$$

The graph showing this relationship is given in Fig.1.

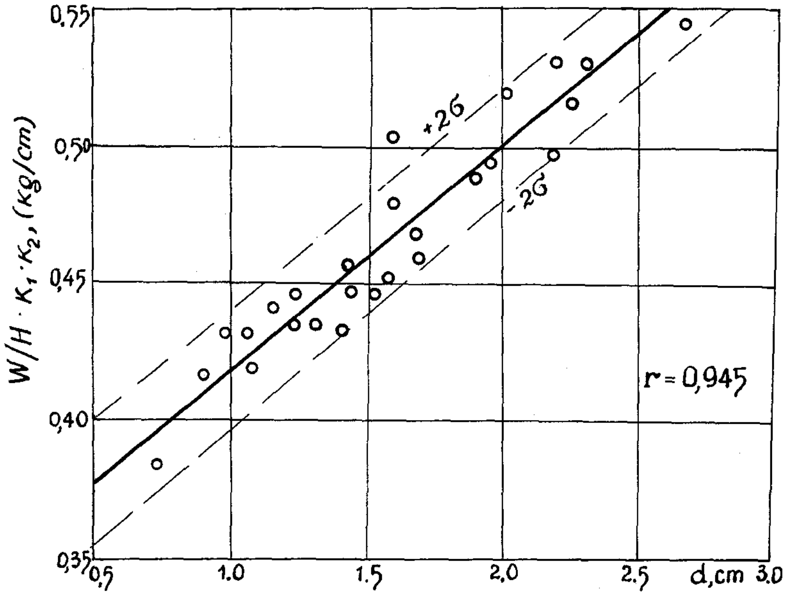

Fig.1. The correlation of soft tissue thickness d and parameters W/H, k_1 and k_2.

Thus, simple measurements of the body parameters make it possible both to assess the thickness of the soft tissue layer covering the thoracic cage and to choose suitable calibration coefficients.

Calibration Procedure

The lungs,liver and skeleton are the chief sites of ^{210}Pb, ^{239}Pu and ^{241}Am deposition in human body. Suitable sets of calibration coefficients are required for the assessment of burdens of these radionuclides in the said organs on the basis of in vivo measurements.

100 point emitters of known activity were placed uniformly alternately throughout the models of the lungs and liver. The distribution of ^{210}Pb or ^{241}Am emitters in skeletal bones is given in Table 3. Measurements in the four points, i.e. the left lung,the right lung, the liver and the skull , were carried out for each insertion of the emitters into one of these models. The pulse count rate was registered at 10-25 keV for calibration with respect to ^{239}Pu, 10-25 keV and 25-70 keV (^{241}Am) and 30-35 keV (^{210}Pb).

The data of the standard calibration of NaI scintillation counter (S=177 cm^2 and h=0.1 cm) for a 1.7 cm - thick soft tissue are given in Table 4.

Table 3.

Distribution of activity in the skeleton

Bones of skeleton	Weight %%	Quantity of sources		Activity nCi
		11 nCi	2nCi	
Skull	14.1	50		550
Chest Cage	15.3		210	588
1.Sternum	1.2		16	44.8
2.Ribs	9.1		126	352.8
3.Clavicles	1.2		16	44.8
4.Scapulae	3.8		52	145.6
Vertebral Column	9.0	38		418
1. Cervical	1.4	5		55
2. Thoracic	4.2	I4		I54
3. Lumbar	3.4	I2		I32
4. Sacrumu	2.0	7		77
Pelvis	7.8	27		297
Arms	16.2	56		6I6
1. Radii	5.9	20		220
2. Ulnae	4.4	I6		I76
3. Hands	5.9	20		220
Feet	35.6	I26		I386
Femora	15.7	56		6I6
Tibiae	14.2	50		550
Feet	5.7	20		220
Total	100	297	210	3855

The sets of calibration coefficients for soft tissue thicknesses from 0.5 to 3.5 cm for scintillation and proportional counters are given in our paper "Dosimetric Monitoring of Content ofthe Radionuclides with a Low Radiation Energy in the Human Organism"

The total error for calibration coefficients (Table 4) due to the variations in the organ shape, the different location of the organs in the phantom the detector displacement with respect to the phantom front wall, the counting statistics and the precision of emitters' calibration is 16% for ^{239}Pu; 8% - for ^{210}Pb and 6% - for ^{241}Am.

The error due to the assumption of the uniform distribution of the assayed radionuclide throughout the organ was determined separately. The values of calibration coefficients for different patterns of radionuclide distribution in the lung model are shown in Tables 5 and 6.

Table 4

Calibration Factors for Homogeneous Distribution cpm/nCi/d=1.7cm

Source position	Counter position	Radionuclides and energy band			
		^{239}Pu	^{210}Pb	^{241}Am	
		10-25	30-55	10-25	35-70
Left lung	left lung	0.120	3.1	8.5	40.0
	right lung	0.004	0.7	2.5	8.4
	liver	0.04	0.2	0.7	2.0
Right lung	left lung	0.004	0.7	2.5	8.4
	right lung	0.120	3.1	8.5	40.0
	liver	0.006	0.4	1.6	5.0
Liver	left lung	0.003	0.8	2.1	10.0
	right lung	0.016	1.4	3.3	18.0
	liver	0.040	1.8	5.9	22.6
Skeleton	left lung		0.22		3.6
	right lung		0.22		3.6
	liver		0.15		1.7
	skull		0.40		7.5

Table 5

Calibration Factors (cpm/nCi, d=17 cm) for ^{241}Am 35-70 keV

Position		Emitter distribution in the lung			
Emitters	Detectors	Uniform	Upper part	Lower part	60% in lymphatic nodes; 40%-uniform
Left lung	Left lung	40.0	35.0	43.0	42.0
	Right lung	5.4	7.9	8.7	8.3
	Liver	2.0	1.2	2.3	1.9

Table 6

Calibration Factors (cpm/nCi, d=1.7 cm) for ^{239}Pu/10-25 keV

Position		Emitter distribution in the lung			
Emitters	Detectors	Uniform	Upper part	Lower part	60% in lymphatic nodes;40% -uniform
Left lung	Left lung	0.120	0.085	0.130	0.105
	Right lung	0.004	0.003	0.003	0.003
	liver	0.004	0.001	0.005	0.003

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