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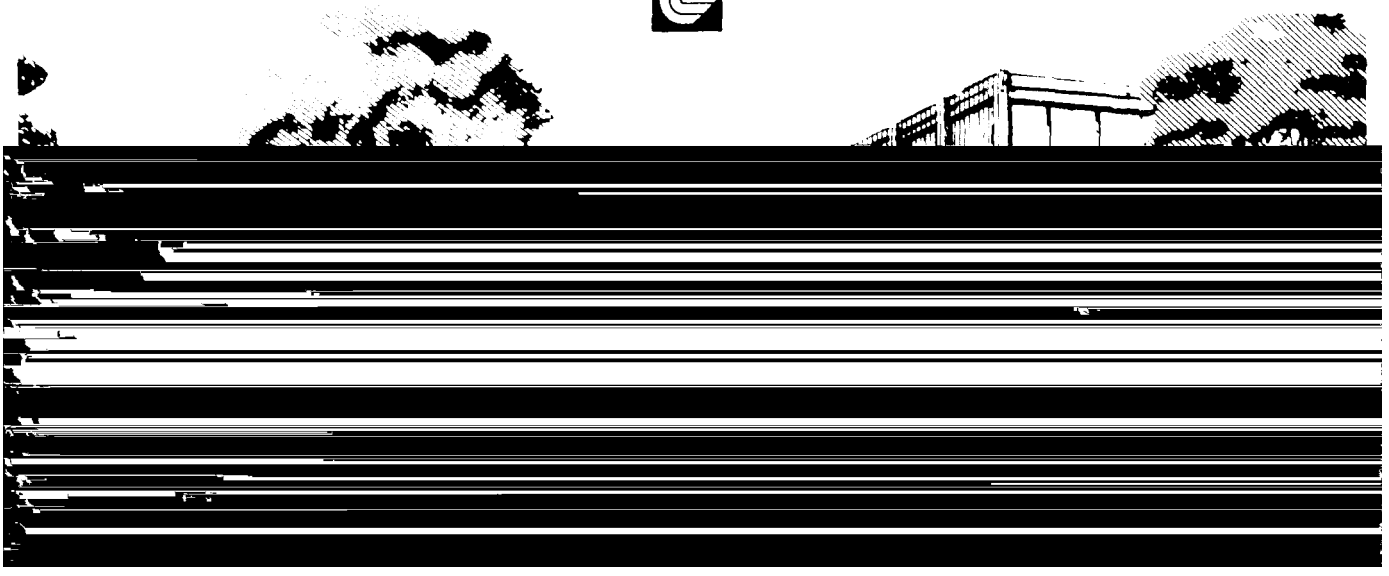

DESIGN CRITERIA FOR PHANTOMS FOR CALIBRATION OF EXTERNAL DETECTORS FOR THE IN-VIVO ASSAY OF PLUTONIUM

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ABSTRACT

The proper medical control of plutonium requires periodic evaluation of the lung burden of chronically exposed process workers. Instruments developed for this purpose and currently in use cannot detect levels below about one-half to one maximum permissible lung burden. Confidence in such measurements is limited by inadequacies in present calibration techniques. Most laboratories use different phantoms and different calibration methods; results from measurements on the same individual vary widely from one laboratory to another. A program has been organized to develop methods of intercalibrating laboratories engaged in the in-vivo assay of transuranic elements. The first phase of the program has been completed. The response of instrumentation and detectors to point sources of activity was determined in a number of laboratories. Current efforts are being directed toward the design and construction of a phantom to be used specifically for the calibration of detectors for the in-vivo detection of x- and low-energy gamma-ray emitters in the human lung.

INTRODUCTION

The production and the use of transuranic nuclides, primarily plutonium, are steadily increasing. Proper health-physics control of these materials requires the development of reliable, accurate methods of detecting and quantitating small amounts in the human body. Since the usual method of exposure is by inhalation of insoluble forms of the nuclides, recent emphasis has been given to detecting material in the lung through external counting. This is a difficult assignment, since the photon emission of most transuranic nuclides consists predominantly of x-rays below 25 keV. Table I lists the photon emissions of the three most important isotopes, ^{238}Pu, ^{239}Pu, and ^{241}Am [1]. The x-rays are heavily absorbed in tissue, the half-value layer

at 17 keV being about 5 mm. Figure 1 shows the transmission through soft tissue of x-rays from the decay of ^{238}Pu and ^{241}Am, and of the 60 keV gamma-ray of ^{241}Am. The 60-keV gamma-ray has a much greater half-value layer, over 5 cm, and is consequently much easier to detect, The x-rays present by far the greater detection problem.

Ultrasonic measurements have shown that the average thickness of the chest wall in the adult male varies from about 10 to 40 mm [2,3,4]. This results in transmission of 25 to 0.7% of the x-rays from plutonium. When geometrical effects are included, a detector would intercept only a few (1 to 3) x-rays per minute for an average person with a maximum permissible lung burden, 16 nCi. Detectors have been developed with sufficiently high sensitivity and low backgrounds for the detection of these low photon-count rates. They consist mostly of assemblies of thin inorganic scintillators (phoswiches) [5,6] and proportional counters [7,8,9,10]. The proportional counters have better energy resolution than the scintillators but poorer efficiency, especially above about 30 keV. Large solid-state detectors, principally intrinsic germanium, are also under investigation. They have excellent energy resolution but suffer from poor geometrical efficiency due to their small size. The use of many such detectors in arrays could overcome this problem but only at a large monetary expense.

METHOD

Once the x-rays have been detected and their number quantitated, the most difficult task lies ahead, namely conversion of the counts observed to the lung burden in nanocuries. This is accomplished by a procedure referred to as calibration; it can be performed in a number of ways. The simplest but least suitable is to use a point source in a fixed position, correcting to an actual situation by applying appropriate geometrical correction factors, which are difficult to obtain. The two ^{238}Pu curves in Fig. 1 illustrate why this correction is necessary. The lower dashed curve is for a small disk source, the solid line for a mock lung (2600 cm^3) made of plastic and uniformly labeled with the isotope. Another method, and most popular, is to use an anthropomorphic phantom constructed to some "standard man" geometry. Many such phantoms have been developed with varying degrees of complexity [11,12,13]. Some calibrations have been performed with cadavers [5,10,14] and with "in-vivo" methods [15,16].

Regardless of the method of calibration, it is readily apparent from Fig. 1 that a single calibration factor is not appropriate. Most investigators compensate for the thickness effect by using a single calibration point on the phantom, with a known chest wall thickness, and a transmission curve like that in Fig. 1 to derive the counting efficiency as a function of chest wall thickness. This is not completely satisfactory for several reasons. First, no allowance is made for nonuniform distribution of radioactive material in the lungs. Second, with the detectors positioned over the lungs, the count rate due to material in other organs (e.g., liver, lymph nodes) cannot be ascertained. Finally and most important, the phantoms used in most laboratories in the United States were not designed for calibration with x-ray emitters. For example, the REMAB phantom (Alderson Research Laboratories) used at Lawrence Livermore Laboratory (Fig. 2) nominally

is constructed to "standard man" dimensions overall; however, the incorporated skeleton has a small rib cage. This necessitates the use of somewhat smaller "lungs" than desired and results in an incorrect chest wall profile. Figure 3 shows cross-sectional views of the chest as measured ultrasonically, both for the phantom and for an average plutonium worker at this Laboratory [17]. The scans were made across the chest at 5 cm above the level of the nipple. The discrepancy is immediately apparent. The phantom profile is irregular with much too thick a chest wall. Also, the heart is positioned in such a manner that it covers an abnormally large portion of the left lung. Figure 4 shows the chest wall thickness at several points on the chest for both the phantom and the human subject. The circles enclose the portion of the chest surface covered by the detectors used at this Laboratory, two 13-cm diameter phoswich assemblies. Also shown is the percent transmission of Pu x-rays at each point, illustrating the large variation in this parameter. It shows how necessary it is to make careful measurements at many points for determinations of the average chest wall thickness to be used to derive the counting efficiency for any particular subject. The average thickness for the phantom is 42 mm with a range of 34 to 60 mm compared to 28 mm and a range of 22 to 50 mm for the human subject. The corresponding average transmissions are 1.3% to 4.8%.

The difficulties inherent in calibrating detectors for chest counting have been known for some time. Several efforts have been made recently to develop methods of intercalibration among the many laboratories engaged in the in-vivo assay of plutonium. These efforts have included the use of point sources to test the instrumentation [18], and analysis at several laboratories of the same persons, either accidentally exposed plutonium process workers [19] or other personnel intentionally exposed to a mixture of ^{103}Pd and ^{51}Cr [20]. The point-source study was designed to test the performance of counting instruments in various geometries and with a wide range of count rates (over two orders of magnitude), as well as to compare absolute standards. This exercise showed that there is good instrumental control at the participating laboratories; the major discrepancies appeared to be in the activities of the primary laboratory standards. All laboratories have now been provided with standard sources (National Bureau of Standards) so that all future intercalibration efforts will have a common basis for comparison. In the latter exercise a known mixture of ^{103}Pd (20.2 keV and 22.8 keV x-rays, 17-day half-life) and ^{51}Cr (323 keV gamma-ray, 27-day half-life) was inhaled by three persons of different physical stature. The ^{51}Cr, easily measured by conventional whole-body counting techniques, was used as a "tag" for the ^{103}Pd, which could then in principle be used to calibrate the chest counter. Although there was good agreement among many laboratories on the lung burdens of ^{51}Cr, there were large discrepancies in the estimates of ^{103}Pd lung burdens and in the plutonium calibration factors derived therefrom. These differences are attributed primarily to differences in calibration techniques.

In recognition of a need for a coordinated program in this field, the intercalibration effort within the United States was formalized in 1974 through the organization of an "Intercalibration Committee for Low-Energy Photon Measurements," composed of representatives from Argonne National Laboratory, Battelle Pacific Northwest Laboratories, Lawrence Livermore Laboratory, Los Alamos Scientific Laboratory, Mound Laboratory (Monsanto),

and Savannah River Plant (DuPont), sponsored by the Energy Research and Development Administration (ERDA). The primary objectives of the Committee are to develop methods of improving the sensitivity of detector systems for assaying transuranium elements in the human lung, to identify and resolve current weaknesses in the calibration techniques, and to execute a program to intercalibrate the detector systems in use at ERDA-supported laboratories.

In its initial meetings the Committee concluded that the phantoms currently used in calibrating detectors are mostly inadequate; they were not designed for use with x-ray emitters in the lung. The Committee, therefore, has undertaken the design and construction of a more realistic phantom. This phantom will permit a detailed study of the effect on counting efficiency of the distribution of the radioactive material in the lung. After the phantom has been carefully studied, it will be circulated among the interested laboratories and hopefully will become a primary standard for the intercalibration program.

The Committee considered several alternative approaches to the design of the phantom. Initially, the following criteria were established for the phantom:

1. Reference (Standard) man [21,22,23] dimensions to be used where possible.

2. To represent upper trunk only (neck to waist).

3. To contain all pertinent organs, including heart, liver, lungs, kidneys, spleen, lymph nodes, trachea.

4. To contain a human skeleton (Caucasian) with marrow cavity filled with unit-density material.

5. All organs to be easily removable.

6. Tissue equivalent materials to be used throughout, with a lung density of 0.25 g/cm^3.

7. Average chest wall thickness and chest profile to be changeable.

A survey has been made of all relevant data required to design a phantom to a specific geometric shape. Table II presents the data for standard man, for personnel counted for plutonium at this Laboratory and at Los Alamos, for a REMAB phantom and a cadaver. Since there is such a large difference between the standard man and our own average-worker data, it was decided to use the average dimensions for employees routinely measured for plutonium, augmented with standard-man data where necessary. The other criteria have not been changed.

The Committee considered two approaches to the development of the phantom. The first involves the use of anatomical cross sections as presented by Eycleshymer and Schoemaker [24]. The cross sections were photographed at suitable enlargement to produce life-sized copies. These copies were then

used as patterns for cutting individual sections from 25-mm-thick polyurethane foam. The sections were stacked to produce a life-sized phantom. This rather crude figure was built up with modeling clay by a sculptor to make the phantom as lifelike as possible. The same enlarged cross sections were used also to construct a phantom of the interior of the body, with each organ individually formed. These phantoms, which are models only and not final versions, are now complete. Eventually they will be combined to produce a single phantom.

The second approach, preferred by the Committee, is to model the phantom from a human cadaver selected to match closely the dimensions of the average plutonium process worker. Such a cadaver has been obtained; the dimensions are listed in Table 11. In preparation for constructing the plastic phantom, plaster casts have been made of the exterior and interior surfaces of the torso and of the major organs. The skeleton was removed and cleaned in preparation for filling the marrow cavity with a unit-density material, MIX-D [25]. After considerable study of "tissue equivalent" materials, it was decided to make the soft tissues of the phantom, including the muscle and internal organs, of polyurethane plastic or a depolymerized rubber similar to Temex [26] with absorption characteristics matched as closely as possible to those of real soft tissue (i.e., beefsteak). The lungs will be formed from a foamed version of the same material if feasible, otherwise from RANDO lung stock, with a density of 0.25 g/cm^3. Since plutonium at late times after exposure translocates to the lymph nodes, a hollow trachea and the three major lymph node regions will also be included, as shown in Fig. 5. This means that the phantom can be used to calibrate intraesophageal probes used to detect plutonium in the lymph nodes [27]. Since the heart in the cadaver is somewhat enlarged, both it and the left lung must be remodeled to some extent.

As described earlier the average chest wall thickness varies considerably in our worker population; this applies to the chest thickness profiles as well. Figure 6 shows an ultrasonic scan of an individual, transverse to the body at 5 cm above the level of the nipple. The data shown in Figs. 4 and 7 were taken from such scans. A large number

SUMMARY

An "Intercalibration Committee for Low-Energy Photon Measurements" has been formed, under the sponsorship of the United States Energy Research and Development Administration, to coordinate the efforts at intercalibration among this country's laboratories actively engaged in measurements of transuranic nuclides in the human lung. This Committee has undertaken initially to correct what it believes to be a major weakness in this field, namely the lack of a phantom adequate for use wirh x-ray emitters. The Committee has designed such a phantom and it is now under construction at the Lawrence Livermore Laboratory.

ACKNOWLEDGMENTS

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TABLE I

Photon emission from three transuranic isotopes

Isotope	Energy, keV		Intensity, number/decay
^{238}Pu	L x-ray	~17	0.115
	y-rays	43.50	3.4×10^{-4}
		99.84	9.4×10^{-5}
		152.71	1.0×10^{-5}
^{239}Pu	L x-rays	~17	0.0465
	y-rays	38.7	2×10^{-5}
		52.0	7×10^{-5}
^{241}Am	L x-rays	~17	0.376
		26.3	0.025
		43.4	7×10^{-4}
		59.5	0.359

TABLE II

Dimensional data on "standard man", laboratory personnel, a REMAB phantom, and a cadaver.

Parameter	Standard man	Average worker	REMAB phantom	Cadaver
Height	170 cm	177 cm	-----	175 cm
Weight	70 kg	76 kg	-----	76 kg
Chest circumierence	-----	100 cm	-----	101 cm
Liver	1700 g	-----	1600 g	2000 g
Lungs	1000 g	-----	649 g	543 g
Kidneys	300 g	-----	266 g	301 g
Heart	300 g	-----	365 g	702 g
Spleen	150 g	-----	138 g	120 g

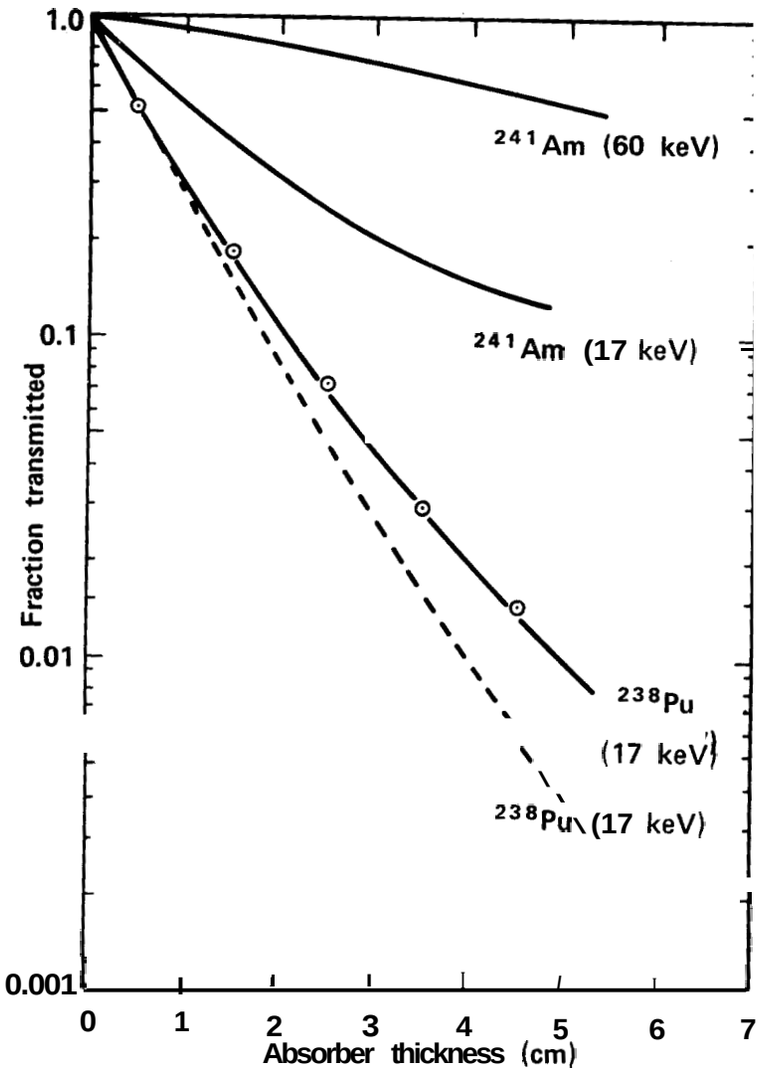
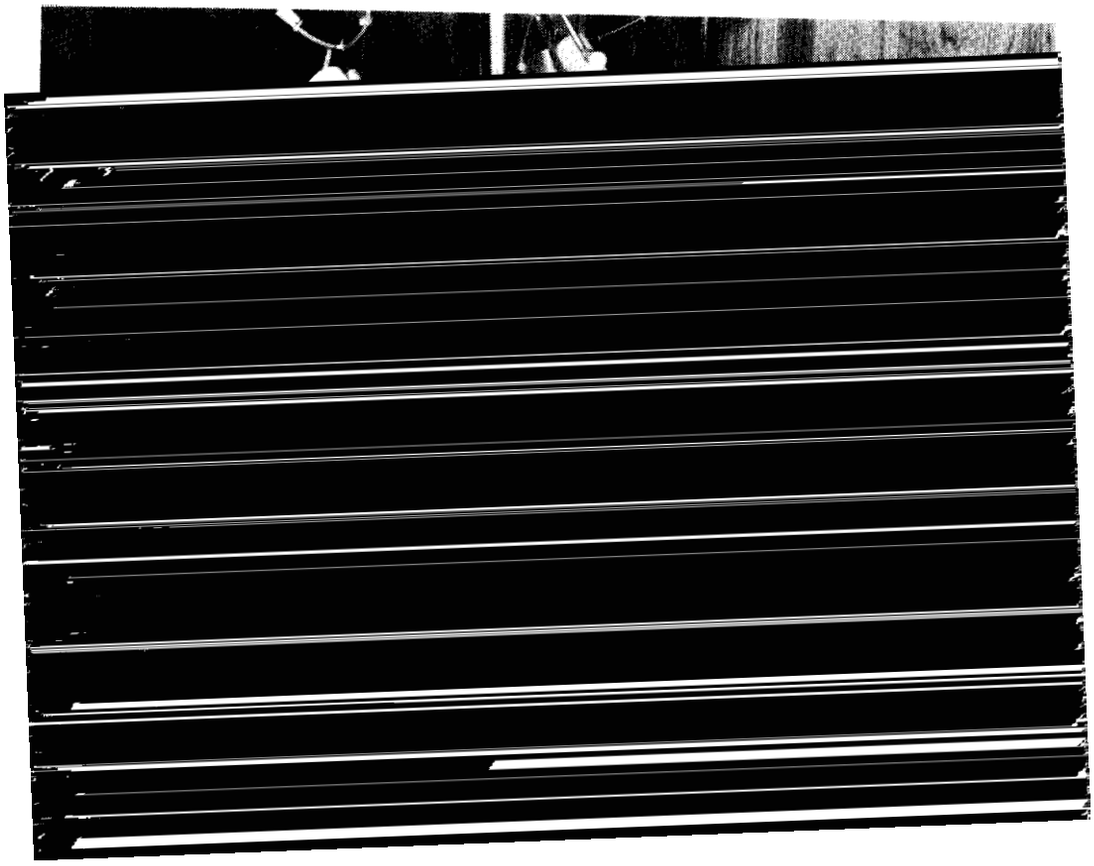
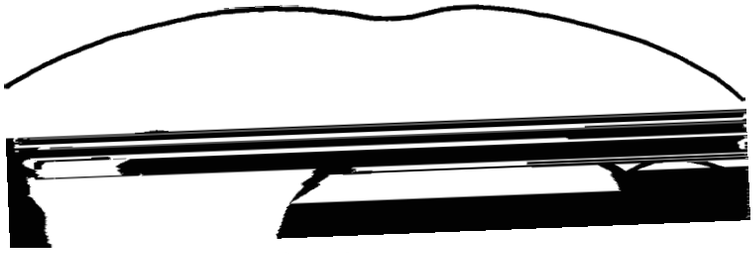
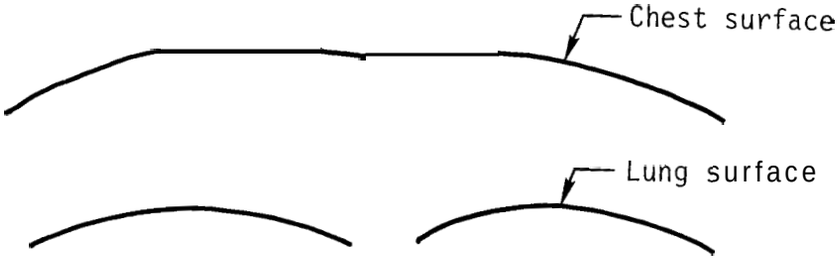


Fig. 1. Fraction of photons transmitted as a function of absorber thickness for ^{238}Pu and ^{241}Am. Of the two curves for ^{238}Pu, the dashed line is for a very small source and the solid line is for a plastic mock lung of 2600 cm^3 uniformly loaded with the isotope.





REMAB phantom



Human subject

Fig. 3. Chest thickness profile for a human subject and a Rando phantom, measured transverse to the spine 5 cm above the level of the nipple.

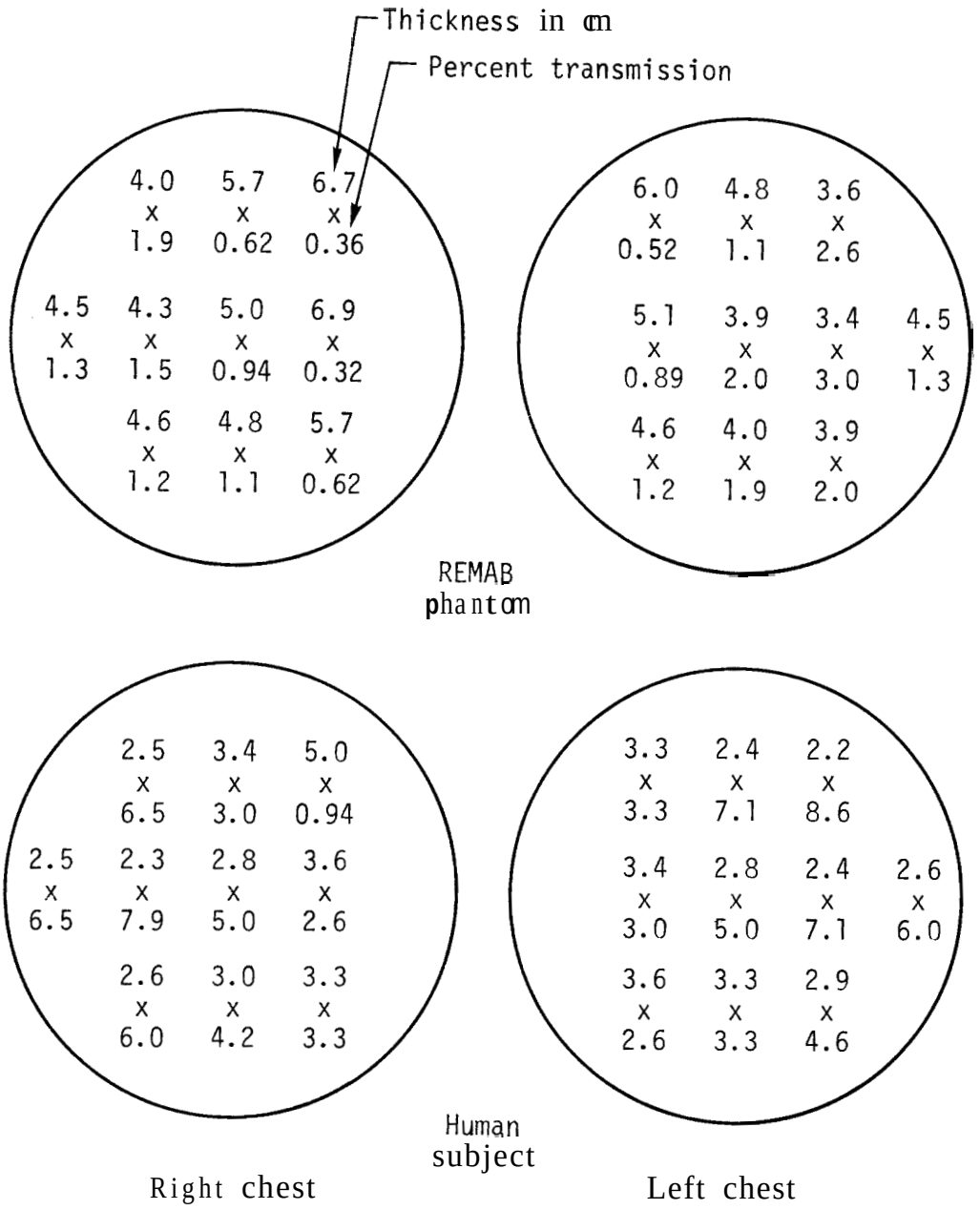


Fig. 4. Chest wall thickness in cm (upper number) and percent transmission (lower number) at selected points within 13 cm diameter circles, for the REMAB phantom and a human subject. The circles correspond to the areas covered by the scintillation counters.

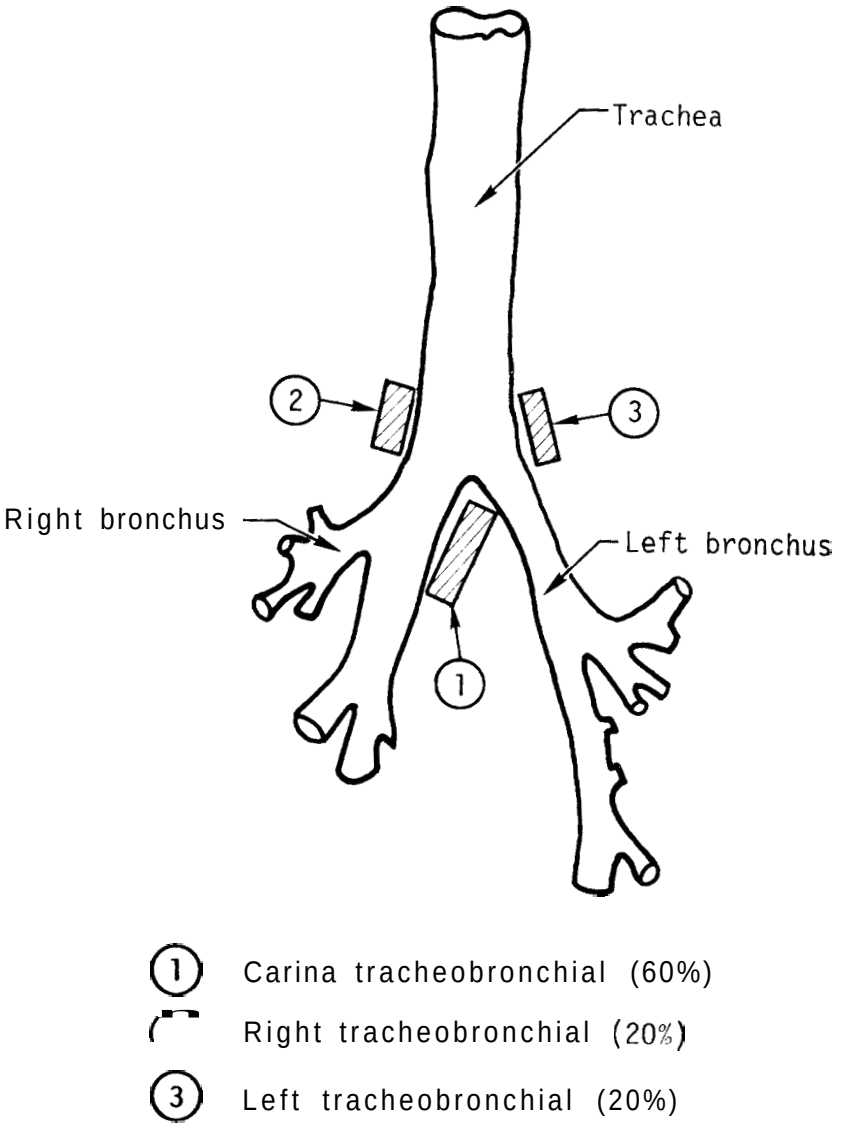


Fig. 5. Schematic drawing of the trachea and lymph nodes to be included in the phantom, as described in the text. The percentage values refer to the relative amount of the isotope to be included in each node.

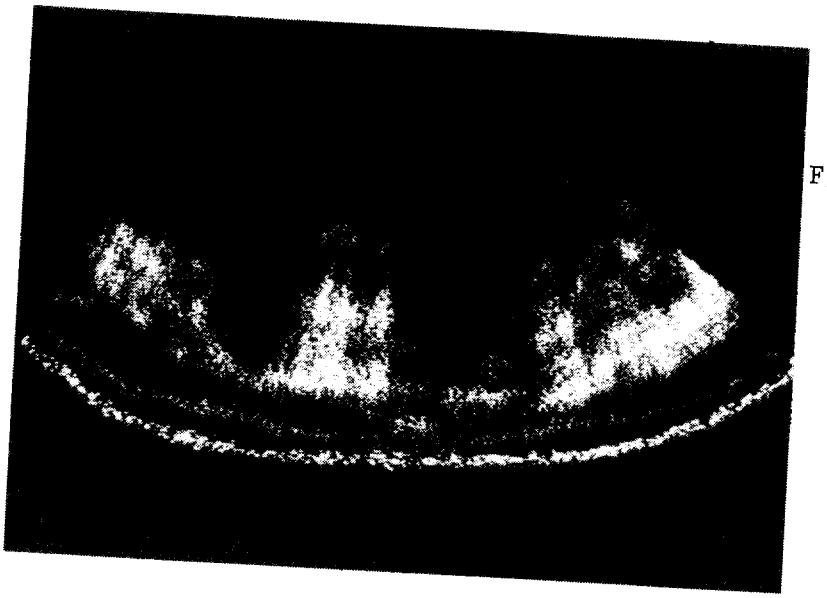


Fig. 6. Ultrasonic scan of a human chest (B scan mode) transverse to the spine 5 cm above the nipple. The ribs, fat layers, and the chest and lung surfaces are all visible.

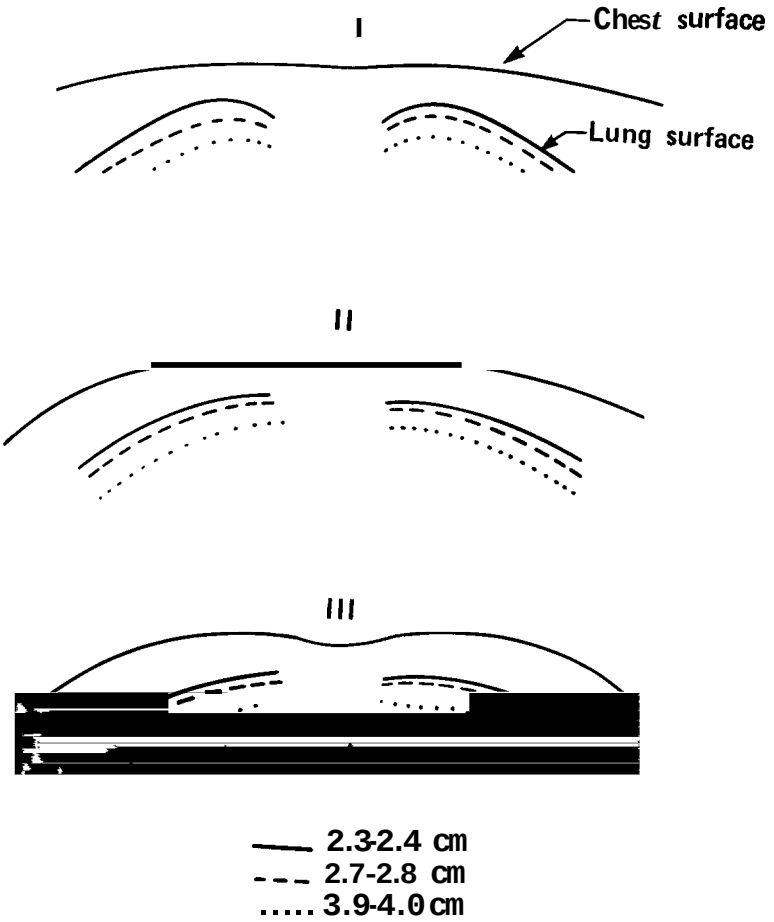


Fig. 7. Average chest thickness profiles transverse to the spine of three different locations on the chest, for three average chest thickness ranges. The curves labeled I, II, and III are for 9, 5, and 1 cm above the nipple respectively.