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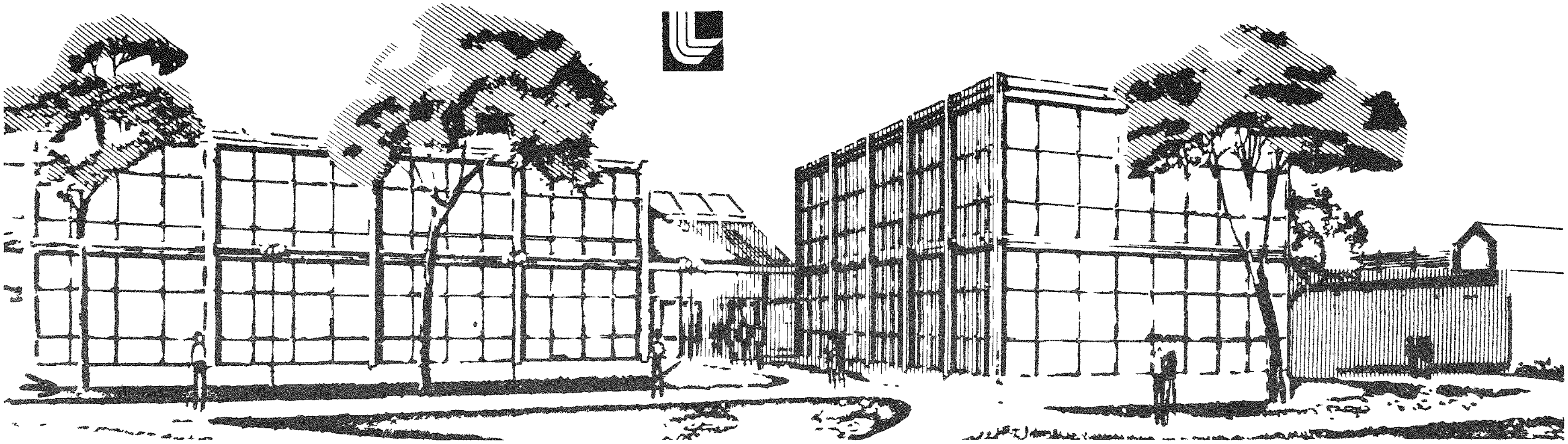

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# FABRICATION OF A TISSUE-EQUIVALENT TORSO PHANTOM FOR INTERCALIBRATION OF IN-VIVO TRANSURANIC-NUCLIDE COUNTING FACILITIES*

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ABSTRACT

A tissue-equivalent human-torso phantom has been constructed for calibration of the counting systems used for in-vivo measurement of transuranic nuclides. The phantom contains a human male rib cage, removable model organs, and includes tissue-equivalent chest plates that can be placed over the torso to simulate people with a wide range of statures. The organs included are lungs, heart, liver, kidneys, spleen, and tracheo-bronchial lymph nodes. Polyurethane with different concentrations of calcium carbonate was used to simulate the linear photon-attenuation properties of various human tissues — lean muscle, adipose-muscle mixtures, and cartilage. Foamed polyurethane with calcium carbonate simulates lung tissue. Transuranic isotopes can be incorporated uniformly in the phantom's lungs and other polyurethane-based organs by dissolution of the nitrate form in acetone with lanthanum nitrate carrier. Organs have now been labelled with highly pure $^{238}$Pu, $^{239}$Pu, and $^{241}$Am for calibration measurements. This phantom is the first of three that will be used in a U.S. Department of Energy program of intercomparisons involving more than ten laboratories. The results of the intercomparison will allow participating laboratories to prepare sets of transmission curves that can be used to predict the performance of their counting systems for a wide range of subject builds and organ depositions. The intercomparison will also provide valuable information on the relative performance of a variety of detector systems and counting techniques.

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## INTRODUCTION

One of the most difficult health-physics problems is the accurate and sensitive in-vivo measurement of $^{239}$Pu and other transuranic nuclides in the human body. Low photon-emission rates, absorption of the low-energy photons by bone and soft tissue, uncertainties in estimate of internal deposition patterns, and low permissible organ burdens (for example, 16 nCi (592 Bq) $^{239}$Pu in lung) make detection and quantification of transuranics at health-protection levels difficult.

A key aspect of the in-vivo assay problem is the need for a realistic phantom that: reproducibly simulates the counting geometry of internally deposited radionuclides, is made of materials that simulate the photon-attenuation properties of human tissues (muscle, bone, adipose, cartilage, and lung) at energies below 20 keV, and is rugged enough to be used in comparing the performance of counting systems at a number of widely separated laboratories.

The first of three phantoms has now been completed at the Lawrence Livermore Laboratory (LLL). Phantom-construction criteria are based on requirements established by the U.S. Department of Energy Intercalibration Committee for Low-Energy Photon Measurements [1]. This committee is composed of whole-body-counting specialists from Argonne National Laboratory, Battelle Pacific Northwest Laboratories, Lawrence Livermore Laboratory, Los Alamos Scientific Laboratory, Mound Laboratory (Monsanto),[1] Rocky Flats Plant (Rockwell International), and Savannah River Plant (Du Pont).

The phantom simulates a human male torso without head or arms and is terminated just above the pelvis. The stature is that of a man 1.77 m tall, weighing 76 kg. The phantom consists of a tissue-equivalent (TE) polyurethane torso shell with an imbedded human male rib cage. Tissue-equivalent lungs, heart, liver, kidneys, and spleen, with additional TE material simulating intestines and body fluids, fill the phantom abdominal cavity. We have made chest plates of TE material that can be overlaid on the phantom to simulate the geometry and chest-wall attenuation of the range of statures seen in male radiation workers. Two sets of chest plates have been made in order to simulate tissue attenuation provided by lean muscle or by a combination of adipose and muscle (50% of each by weight).

Uniform deposition of transuranic isotopes in an individual organ can be simulated by labelling the TE organ with the appropriate materials. We have now made sets of lungs and lymph nodes that are each labelled with highly pure $^{238}$Pu, $^{239}$Pu, or $^{241}$Am (Table I). By placing the labelled organs in the phantom, we can make measurements with and without chest plates and acquire data that can be used to develop counter-calibration curves for each of the isotopes of interest. The phantom includes a 1-cm-diameter channel behind the tracheo-bronchial plane so that calibrations can be made with esophageal detectors.

## TISSUE-EQUIVALENT MATERIAL

Radiologists and whole-body-counting specialists have used various materials to simulate tissue. The selection includes readily available materials such as Lucite, Perspex, Presdwood, polyethylene, and even

[1]Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

water. However, when low-energy x rays are involved, the radiation-attenuation properties of human tissue must be simulated more carefully. Even differences in attenuation between soft tissues such as muscle, adipose, and cartilage become important. To precisely simulate these attenuations, other researchers have developed some specific TE material formulations. These include: Mix-D, a mixture of paraffin, polyethylene, titanium oxide, and magnesium oxide [2]; Temex, a depolymerized rubber [3]; and Rando muscle-equivalent material, a rigid filled epoxy.[2]

None of these materials were satisfactory for construction of the intercalibration phantom because we required that: the tissue simulation be accurate at energies as low as 15 keV for tissue thicknesses greater than 4 cm, the TE material be easy to form into irregular shapes, and the TE material be durable and not deform significantly over many years. In addition, we must be able to vary the composition of the material to simulate the different soft tissues — muscle, adipose, and cartilage. We also need a lung-tissue simulant that has a density of 0.25 to 0.30 $g/cm^3$. Finally, it is necessary to label the TE materials uniformly with plutonium, americium, uranium, and other heavy elements.

Polyurethane proved to be an appropriate basis for our family of TE materials. With a composition of 9.2% hydrogen, 68.9% carbon, 3.7% nitrogen, and 18.2% oxygen (by weight) and a density of 1.06 $g/cm^3$, polyurethane has linear-attenuation properties that approximate those of tissue with 87 wt% adipose and 13 wt% muscle. By adding small quantities of materials with higher atomic number, such as calcium, we can simulate more dense tissues such as muscle and cartilage. Because there are commercial polyurethane formulations that involve mixing two fluid components, this TE material can easily be cast in quite irregular shapes. There are also commercial formulations that can be used to produce foamed polyurethane with densities in the range needed to simulate lung.

Although we have selected one commercial polyurethane (Scotchcast by the Minnesota Mining and Manufacturing Company), there are other products that would be suitable for solid TE material. We begin making the TE plastic by using a small, laboratory rolling mill to incorporate $CaCO_3$ powder into component A of the polyurethane. Our present TE material formulations call for 2.1 wt% $CaCO_3$ to simulate chest tissue having equal weights of adipose and muscle, 4.3 wt% $CaCO_3$ for muscle simulation, and 5.8 wt% for cartilage simulation.

Our formulation of the lung-equivalent material also involves a two-component polyurethane — 1940D (black), available from the CPR division of Upjohn Corporation. A small quantity of water is added to generate foaming. The specific formulation is 30.0% 1940D component A, 68.4% component B, 0.15% $H_2O$, and 0.15% acetone (by weight), with transuranic tracer. We add 6.2% $CaCO_3$ to component A to achieve the proper x-ray transmission. Under proper conditions, the foam expands uniformly and we can control lung density by the amount of polyurethane poured in the mold. We used lanthanum nitrate carrier for the transuranic nuclides to achieve uniform distribution of the radioactive material in the model lungs. X-ray fluorescence measurements of the lanthanum concentration showed that the carrier distribution in sample lungs was uniform to within ±4% of the average value.

We have measured the photon transmissions of various tissues and TE materials using 16.6-keV x rays from $^{93m}Nb$, L-series x rays from $^{238}Pu$,

[2]Manufactured by Alderson Research Laboratories, Stamford, Connecticut, U.S.A.



and the 60-keV gamma ray from $^{241}Am$. Transmission curves for $^{93m}Nb$ and $^{238}Pu$ are shown in Fig. 1. The $^{241}Am$ transmission through soft tissue, excluding lung, has a very narrow spread — through 4.0 mm of sample, 63.0% for muscle and muscle-equivalent polyurethane to 66.7% for adipose and unloaded polyurethane. The $^{238}Pu$ transmission data show curvature because the three L-series x rays (13.6, 17.2, and 20.2 keV) have different attenuation coefficients.

## FABRICATION TECHNIQUES

The torso and organ molds are all based on solid plaster casts made from a male cadaver provided by the Anatomy Department at the University of California, San Francisco. The cadaver was 1.77 m tall, weighed 75 kg, and had a chest circumference of 1.01 m. In comparison, a random sample of 500 male LLL and Los Alamos Scientific Laboratory employees on the average were 1.77 m tall, weighed 76 kg, and had a chest circumference of 1 m. The organs and TE replicas are shown in Fig. 2. Organ-replica volumes are presented in Table II, together with values for Reference Man [4].

An important part of the phantom construction was modification of the torso casts so that the phantom chest wall overlying the lungs would be as thin as possible while still accommodating the rib cage. (This allows us to measure attenuation for the widest range of chest-wall thicknesses.) We made a thin plastic reproduction of the chest exterior by vacuum forming a plastic sheet on the plaster torso cast. We marked this chest plate with a grid, drilled holes at the grid points, and placed the plate over a cast of the organ cavity. From ultrasonic-scan data taken on the chests and abdomens of a large group of radiation workers and from published anatomical data [5], we tablulated the thinnest realistic profiles of chest- and abdominal-wall thickness, for the phantom. With the plastic chest plate in place on the organ-cavity cast, we mapped the actual chest- and abdominal-wall spacings. The differences between the mapping and the desired profiles were then removed from the plaster torso cast. A silicon-rubber mold for the phantom was made from this cast. The final torso model is shown in Fig. 3 together with its mold.

After removal from the cadaver, the rib cage was cleaned to remove soft tissue. We then used a colony of Dermestid beetles maintained in the Museum of Vertebrate Zoology, University of California, Berkeley Campus, to remove traces of remaining soft tissue. The beetles were particularly useful for this purpose because they have access to small voids in the skeleton (particularly in the vertebrae) but do not attack cartilage. The cartilage was thus saved for future use. Finally, we used ammonia and a vapor solvent to degrease the bones. We used a vacuum filling technique to replace lost marrow in the bone trabeculae with Mix-D tissue simulant. We completed the rib-cage assembly by connecting vertebrae with nylon pins and the ribs with nylon string. Special sections of polyurethane cartilage simulant connect the ribs to the sternum. The rib cage is shown in place on the organ-cavity model in Fig. 4(a). Figure 4(b) shows the rib cage and the organ-cavity model placed in the torso mold before casting.

The final major task in phantom construction was fabrication of TE chest plates, which will be used to simulate the chest-wall attenuation of a wide variety of male statures. Based on requirements established by the Department of Energy Intercalibration Committee [1], we made molds for four chest plate thicknesses: 6, 11, 16, and 24 mm. This allows us to make five measurements covering the range of chest-wall thickness — from 19 mm without chest plates to 43 mm with the thickest plates. This range includes more than 95% of the male radiation workers monitored in the U.S. Two sets of plates have now been cast: one with muscle-equivalent material and one with polyurethane to simulate tissue composed of 50% muscle and 50% adipose. Figure 5(a) shows the phantom assembled with the 11-mm-thick chest plate in place. Figure 5(b) shows the phantom and chest plate apart, and Fig. 5(c) shows the phantom with both the chest plate and torso cover removed.

PHANTOM EVALUATIONS

The success of the phantom in an intercalibration program depends on how faithfully it simulates human morphology and radiation transmission of human tissue. We used a computerized axial tomographic (CAT) scanner at a local hospital to help evaluate these qualities. The CAT scanner yields excellent morpholgical data through cross-sectional scans. It also provides data on the density of tissue in each section. Figure 6(a) shows a typical scan of the phantom through the lung region. The schematic in Fig. 6(b) shows contours of a typical section of the phantom chest and the relative profiles of the four chest plates. Comparative tissue densities measured with the CAT scanner for typical human and phantom tissues are shown in Table III. The CAT scanner data depends on the radiation transmission of the tissue, so the agreement in Table III indicates that the phantom will provide an accurate measurement of internal attenuation.

We have made preliminary body-attenuation measurements with the phantom using two 127-mm-diameter phoswich scintillation detectors placed over the lungs. Data for attenuation of L x rays from $^{238}$Pu are presented in Fig. 7. For comparison, we give data from both muscle-equivalent chest plates and chest plates simulating a combination of muscle and adipose.

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REFERENCES

1. DEAN, P.N., GRIFFITH, R.V., ANDERSON, A.L., "Design criteria for phantoms for calibration of external detectors for the in-vivo assay of plutonium," International Atomic Energy Agency Symposium, Diagnosis and Treatment of Incorporated Radionuclides, IAEA, Vienna (1976) 265.

2. JONES, D.E.A., Brit. J. Radiol. 32 (1959) 68.

3. STACEY, A.J., BEVAN, A.R., DICKENS, C.W., Brit. J. Radiology 34 (1961) 510.

4. Report on the Task Group on Reference Man, International Commission on Radiological Protection, Publication 23, Pergamon Press, Oxford (1975).

5. EYCLESHYMER, A.C., SCHOEMAKER, D.M., A Cross-Section Anatomy, Appleton-Century-Cross Press, New York (1970).

TABLE I. RELATIVE X-RAY CONTRIBUTIONS OF TRANSURANIC NUCLIDES USED TO MAKE LABELLED ORGANS (AS OF 5 AUGUST 1977)

| Contributing nuclide | Relative contribution, Primary labelling nuclide: $^{238}Pu$[a] | $^{239}Pu$[b] | $^{241}Am$[a] |
|---|---|---|---|
| $^{238}Pu$ | 0.999 | 0.003 | ≤0.0002 |
| $^{239}Pu$ | ≤0.0001 | 0.934 | ≤0.0001 |
| $^{240}Pu$ | ≤0.0002 | 0.055 | ≤0.0002 |
| $^{241}Am$ | ≤0.0004 | 0.007 | 0.999 |
| Others | ≤0.0001 | ≤0.001 | ≤0.0001 |
| | 1.000 | 1.000 | 1.000 |

[a]By alpha pulse-height analyses.
[b]By mass spectrometry.



TABLE II. COMPARATIVE ORGAN VOLUMES

| Organ | Volume, $cm^3$: Reference Man[a] | Phantom |
|---|---|---|
| Lungs | | |
| Left | 1762 | 1689 |
| Right | 2153 | 2180 |
| Total | 3915 | 3869 |
| Heart | 742 | 748 |
| Liver | 1700 | 2050 |
| Kidney | | |
| Left | 149[b] | 170 |
| Right | | 150 |
| Spleen | 171 | 155 |

[a]Based on data from Ref. 4.
[b]Distinction between left and right kidneys not made.

TABLE III. DENSITIES OF TISSUE AND TISSUE-EQUIVALENT PLASTIC MEASURED WITH A COMPUTERIZED AXIAL TOMOGRAPHIC SCANNER

| | Density, g/cm$^3$ | |
|---|---|---|
| Tissue | Tissue | TE polyurethane |
| Muscle | 1.06 | 1.09 |
| 87% adipose, 13% muscle | — | 1.01 |
| Adipose | 0.92 | — |
| Lung | 0.31 | 0.28 |

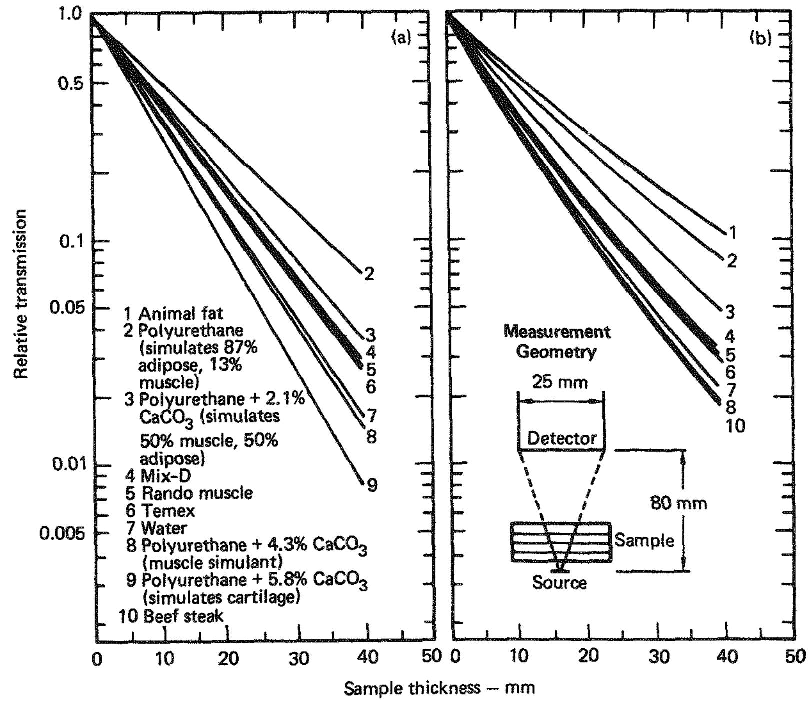


FIG. 1. Relative x-ray transmission through tissue-equivalent materials: (a) 16.6-keV x rays from $^{93m}$Nb, (b) 17-keV L x rays from $^{238}$Pu.

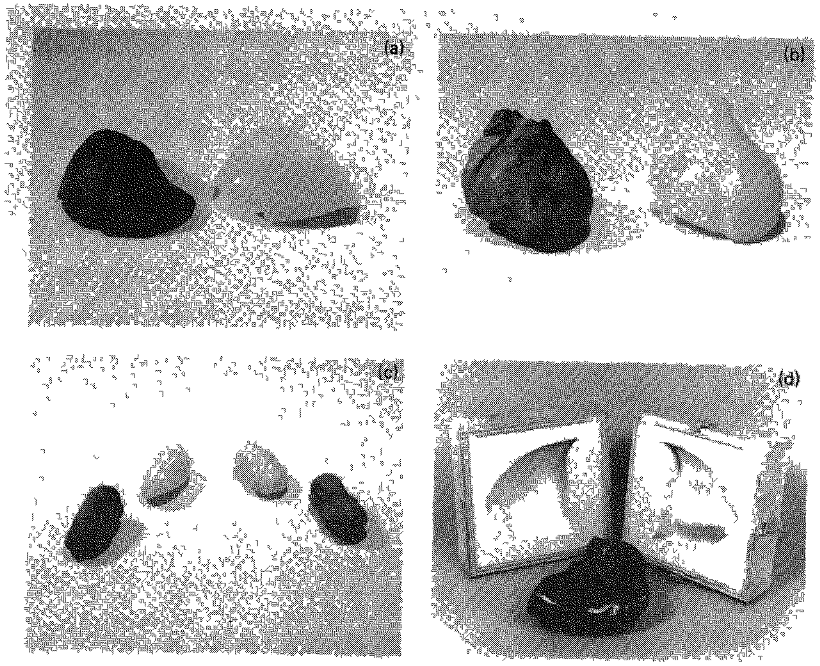


FIG. 2. Comparison of real and tissue-equivalent organs: (a) liver, (b) heart, (c) kidneys, and (d) lung with mold used for casting.

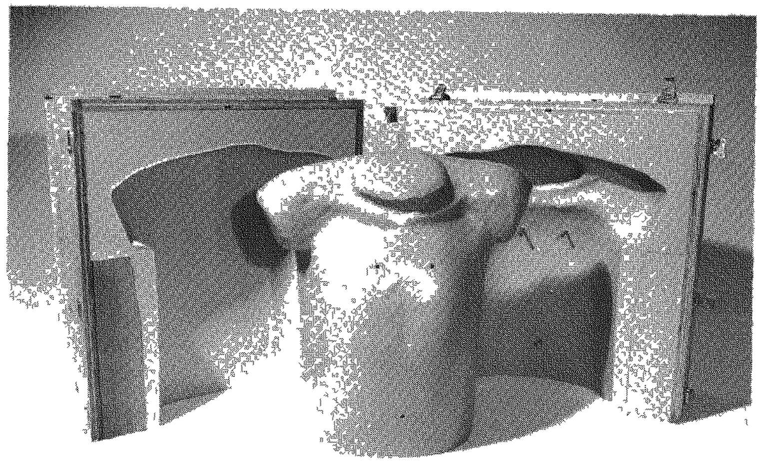

FIG. 3. Final torso form with silicon mold used for phantom casting.

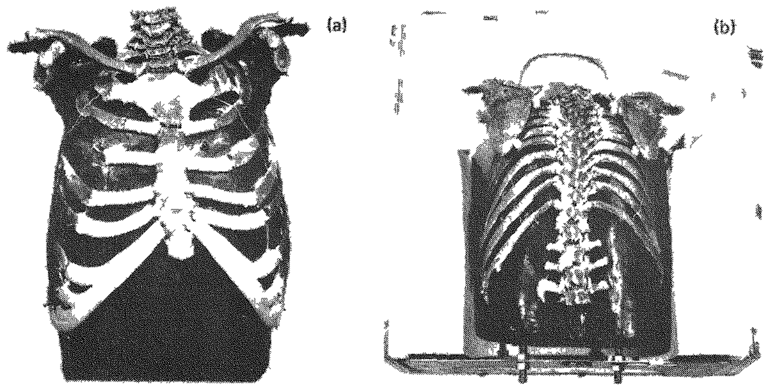


FIG. 4. Phantom organ-cavity cast with rib cage in place (a) front view, (b) rear view, assembly in place in torso mold.

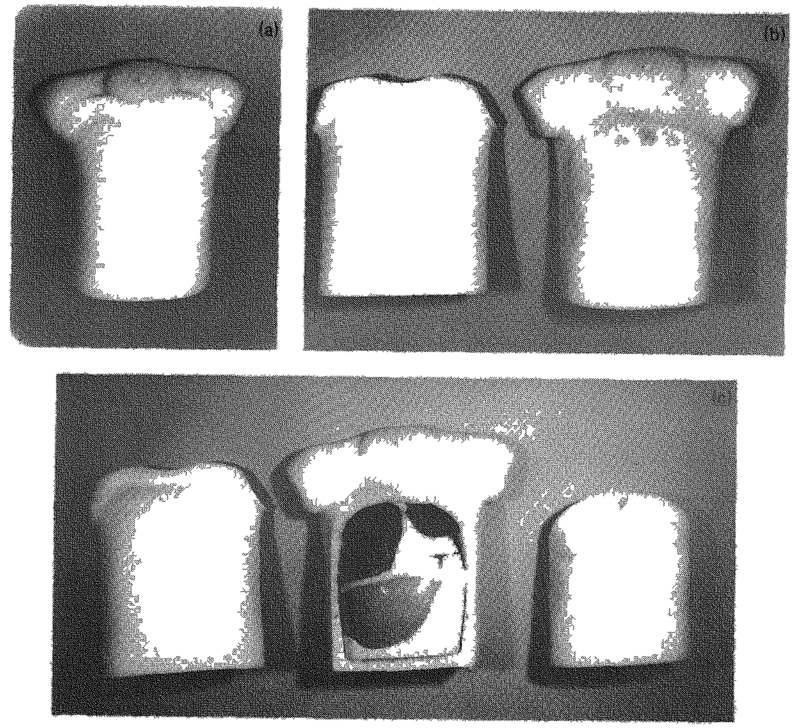


FIG. 5. Completed phantom: (a) with 11-mm-thick chest plate in place, (b) with chest plate removed, and (c) with torso cover removed showing organs.

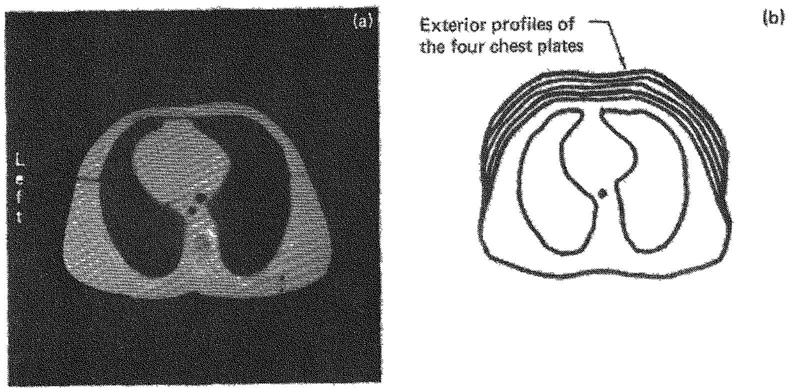


FIG. 6. Phantom contours from computerized axial tomographic (CAT) scanner: (a) display of section through the chest, (b) drawing of section contours with chest-plate profiles.

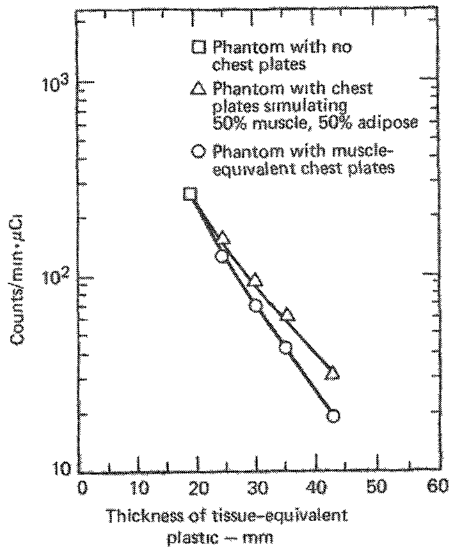


FIG. 7. Sensitivity of two 100-cm$^2$ phoswich detectors to $^{238}$Pu uniformly deposited in phantom lungs.

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