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Further Realistic Torso Phantom Development

Introduction. In previous Hazards Control Progress reports, we discussed the progress on construction of a realistic torso phantom to be used for calibrating detectors designed to measure heavy elements such as $^{239}$Pu in vivo. This report covers further work on phantom construction, including reconstruction of the rib cage, preliminary measurements to establish chest contour, final shaping of the major organs, and investigation of tissue-equivalent (T.E.) material.

Organ Shaping. After dissecting the cadaver that was the source of the phantom rib cage, both the organs and the foam mold of the torso cavity developed some distortion. As a result, the lungs, heart and liver had to be reshaped to assure close fit and compatibility. The lungs in particular had shrunk significantly.

We used the reshaped plaster cast of the torso void to make a plastic female mold that represented the eventual phantom cavity. The plaster lung casts were put in position in the cavity, and plaster was added to fill out each one. In doing so, we used the cavity as a mold for the outside surface of the lungs.

After reshaping the lungs, we reshaped the heart to fit in place between the lungs. Dr. Sexton Sutherland, an anatomist at the University of California Medical Center, San Francisco, guided us in that part of the work. After reshaping the heart, we filled the space between the lungs that would normally contain large blood vessels, esophagus, and trachea with silicon rubber (Fig. 1). That was done as a temporary step so that we could reshape the liver cast. In the phantom, the same space will be filled with muscle-equivalent plastic which has a hollow esophagus and depressions for radioactive “lymph nodes.”

We reshaped the liver cast by adding plaster to conform to the cavity surface at the front of the torso, and removing material from the back of the liver so that the original volume was retained. In the finished phantom the spleen and kidneys will be imbedded, as cast from the originals, in muscle-equivalent material used to simulate absorption by the intestines and other surrounding tissue.

As a result of reshaping, the lung and heart volumes were changed; however, the liver volume is essentially the same. The new lung volumes are 2180 ml right and 1689 ml left, for a total of 3869 ml compared with a published value for “average adult” of 3915 ml. The heart volume was reduced from 865 to 748 ml, compared with an average of 742 ml for 168 adult males. Although the purpose of organ reshaping was better fit, we seem to have achieved more appropriate size as well.

Reconstructing the Rib Cage. We dissected and cleaned the trabecular bone of the rib cage. As a result, the bone marrow was removed. A method for replacing the marrow with MIX-D, a tissue-equivalent wax-based material, had previously been used successfully, so we used the technique to fill all of the bones in the rib cage. The method simply requires submerging the bones in molten MIX-D in an evacuated chamber. The chamber is brought to atmospheric pressure to force the MIX-D into the bones and then they are removed, cooled, and scraped. After scraping, we removed traces of the wax from most of the rib surface by micro-blasting with CaCO$_3$ powder to improve the bond of the polyurethane tissue-equivalent plastic after phantom assembly.

The final step was to assemble the rib cage by drilling fine holes in the ribs and vertebrae so they could be pinned together with nylon tennis racket string. We used nylon squid line to maintain rib spacing and add strength to permit handling. The assembled rib cage is shown on the plaster torso cavity cast (Fig. 2).

Torso Contour. An important part of plutonium measurement in the lungs by external counting is determination of the fraction of low-energy x rays transmitted through the overlying tissue. Differences in human physique can cause very large differences in x-ray transmission. Hazards Control whole-body...
counter operators have adopted an ultrasonic technique used in medicine for organ imaging to measure the thickness of tissue at selected points between lung and detector. The chest thickness for a given person is characterized by an exponential average of tissue thickness at 70 to 80 points under the detectors. When this technique is used, the usual range of adult males is 20 to 35 mm, with virtually all males falling in the range 15 to 45 mm.

On the basis of this information, we have decided to construct the basic phantom with a 15-mm chest wall thickness. We will cover the range of physiques by add-on chest plates of T.E. material in four thicknesses up to a maximum chest wall of about 43 mm.

Because the cadaver had a chest wall thickness greater than 20 mm, we will have to reduce the external torso cast appropriately. Therefore, a clear elastic chest plate was cast from the plaster mold and marked with a grid using 25-mm spacing. We drilled holes at the grid points, then aligned the chest plate over the void mold and rib cage (Fig. 3). We mapped the chest wall thickness i.e., plaster-to-plastic-shield separation over the chest and upper abdomen. The chest plate will be transferred to the original torso cast. The cast can then be reduced at the grid points by the difference between the mapped separations and the desired chest wall thickness, as determined from ultrasonic measurement data for a number of workers.

Tissue-Equivalent Materials. For purposes of phantom construction, “tissue equivalence” means that the linear transmission properties of the material for photons with energies greater than 15 keV will simulate those of tissue. The density, effective atomic number (Z) and electron density all contribute to simulation; however, it is not necessary to match each of those properties to achieve functional simulation.

The tissues to be simulated include bone, muscle, adipose, cartilage, and lung material. The human rib cage provides the necessary bone simulation, but the other materials will be simulated with plastic materials. The muscle-equivalent material will make up the greatest portion of the phantom mass. It will be used for the basic phantom, add-on layers of chest tissue over the lungs, and the major organs except for the lungs. Adipose-equivalent material will be present only in a few add-on layers. Cartilage, which has a density approximately 10% greater than muscle, will be used only to connect ribs to sternum.

We have selected polyurethane for use as the basic material for tissue simulation because of its durability and low Z composition which nominally is 9% hydrogen, 66% carbon, 4% nitrogen, and 20% oxygen, with a density of 1.06 g·cm⁻³. For lung-equivalent material, we plan to use foamed polyurethane with a
Fig. 4. Relative transmission, $^{238}$Pu L x rays.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\rho$ (g·cm$^{-3}$)</th>
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<tbody>
<tr>
<td>Polyethylene</td>
<td>0.93</td>
</tr>
<tr>
<td>Animal fat</td>
<td>0.90</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>1.06</td>
</tr>
<tr>
<td>Lucite</td>
<td>1.18</td>
</tr>
<tr>
<td>Mix-D (LLL)</td>
<td>0.97</td>
</tr>
<tr>
<td>Rando muscle</td>
<td>1.03</td>
</tr>
<tr>
<td>Water</td>
<td>1.00</td>
</tr>
<tr>
<td>Polyurethane +4.3% CaCO$_3$</td>
<td>1.08</td>
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<tr>
<td>Beef steak</td>
<td>1.03</td>
</tr>
<tr>
<td>Frigerio T. E. fluid</td>
<td>1.06</td>
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</table>

Polyethylene is more transparent to low-energy x rays than muscle, so a higher-Z material must be added to reduce the linear transmission to an appropriate value. Preliminary measurements were reported$^2$ with polyurethane containing 3.5 wt% sulfur. Because of the sulfur odor, we have made samples with 4.3% CaCO$_3$ instead of sulfur. A comparison of the attenuation of polyurethane and a number of other tissue-equivalent materials as well as animal tissues and reference liquids are shown in Fig. 4. Compositions for most of these materials appear in Table 1.

Table 1. Elemental composition of tissue-equivalent materials

<table>
<thead>
<tr>
<th>Element</th>
<th>H</th>
<th>C</th>
<th>N</th>
<th>O</th>
<th>Na</th>
<th>Mg</th>
<th>P</th>
<th>S</th>
<th>Cl</th>
<th>K</th>
<th>Ca</th>
<th>Ti</th>
<th>Fe</th>
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<tr>
<td>Polyethylene$^a$</td>
<td>14.4</td>
<td>85.6</td>
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<tr>
<td>Adipose$^b$</td>
<td>12.0</td>
<td>64.0</td>
<td>0.8</td>
<td>22.9</td>
<td>0.051</td>
<td>0.002</td>
<td>0.016</td>
<td>0.073</td>
<td>0.12</td>
<td>0.032</td>
<td>0.002</td>
<td>-</td>
<td>0.002</td>
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<td>Polyurethane$^c$</td>
<td>9.22</td>
<td>68.9</td>
<td>3.71</td>
<td>18.2</td>
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<td>Lucite$^c$</td>
<td>7.57</td>
<td>59.5</td>
<td>32.9</td>
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<tr>
<td>Mix-D$^d$</td>
<td>13.5</td>
<td>77.7</td>
<td>3.4</td>
<td>3.9</td>
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<td></td>
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<td>1.4</td>
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<tr>
<td>Rando muscle$^e$</td>
<td>8.83</td>
<td>64.4</td>
<td>4.05</td>
<td>20.35</td>
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<td>Temex$^f$</td>
<td>9.6</td>
<td>87.0</td>
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<td>1.53</td>
<td>(Zn - 0.45)</td>
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<td>Water$^a$</td>
<td>11.2</td>
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</tr>
<tr>
<td>Polyurethane$^c$</td>
<td>8.82</td>
<td>66.4</td>
<td>3.55</td>
<td>19.5</td>
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<td>1.72</td>
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<tr>
<td>+ 4.3% CaCO$_3$</td>
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</tr>
<tr>
<td>Muscle$^g$</td>
<td>10.2</td>
<td>12.3</td>
<td>3.5</td>
<td>72.9</td>
<td>0.08</td>
<td>0.02</td>
<td>0.2</td>
<td>0.5</td>
<td>0.3</td>
<td>0.007</td>
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<tr>
<td>Frigerio$^h$</td>
<td>10.2</td>
<td>12.3</td>
<td>3.5</td>
<td>72.9</td>
<td>0.07</td>
<td>0.02</td>
<td>0.2</td>
<td>0.32</td>
<td>0.08</td>
<td>0.39</td>
<td>0.01</td>
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<tr>
<td>T. E. fluid</td>
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</tr>
<tr>
<td>Cartilage$^i$</td>
<td>10.4</td>
<td>10.4</td>
<td>2.7</td>
<td>75.2</td>
<td>0.4</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>0.6</td>
<td>0.3</td>
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<tr>
<td>Rando lung$^c$</td>
<td>5.67</td>
<td>74.2</td>
<td>2.02</td>
<td>18.2</td>
<td>0.6</td>
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<td></td>
<td></td>
<td>(Sb - 0.08)</td>
</tr>
</tbody>
</table>

Note: composition of specific sample depends on date of purchase.

$^a$By direct calculation.

$^b$Ref. 6.

$^c$LLL analysis.

$^d$By calculation, 60.8% paraffin
36.4% (CH$_2$)$_n$, 6.4% MgO, 2.4% TiO$_2$.

$^e$Ref. 7.

$^f$Ref. 8.

$^g$Ref. 9.

$^h$Ref. 10.

$^i$Ref. 3.
At this point we need to define more specifically what physical material we intend to use as a reference for simulation. At 15 keV, the linear attenuation of beefsteak and water differ significantly from Frigerio muscle-equivalent fluid. It is unclear which of these best simulates the tissue of the human male chest. Because our beefsteak and water attenuation curves are rather close and because water is universally available as a reproducible absorber, we have chosen to use water as our transmission standard for lean tissue or muscle. The reference for cartilage will then be the...
absorption by a thickness of water 10% greater than the physical thickness simulated (an equivalent density of 1.10 g·cm⁻²). For lung-equivalent material, we will use absorption by a layer of water having a thickness 25% of the physical thickness of lung simulant (i.e., an equivalent density of 0.25 g·cm⁻²). We have not yet chosen an adipose reference.

**Work Remaining.** After reshaping the chest contour we will cast the torso shell, including the rib cage. We will have to develop a technique for making polyurethane foam lungs with the proper density (≈0.25 g·cm⁻²) and loaded with microcurie quantities of plutonium. All the organs will be cast in T.E. plastic, and T.E. material will be used to simulate absorption of body tissue other than major organs. We will have to make specific provisions for the esophagus and lymph node spaces.

**Acknowledgments.** We wish to thank Norm Boyer and Robert Taylor in the plastics shop and Charles Harder in Hazards Control for their support.

**Albedo Neutron Dosimeter Development**

Work previously reported¹¹,¹² covered studies of the response of an albedo-type neutron dosimeter to various neutron source and moderator configurations. This work has been expanded to include several different badge configurations. Figure 5 depicts the badge designs evaluated in this manner. The dosimeter was exposed while in contact with polyethylene water-filled phantoms 166 mm thick, 267 mm wide, and 180 mm high. Figure 5(a) is the design previously reported. Figure 5(b) is a modified version of the dosimeter designed by Hankins while at LASL,¹³ including a TLD-600/700 pair on top of the normal dosimeter package. Figure 5(c) is similar to that developed by Boggs.¹⁴ It consists of a TLD-600/700 pair shielded from incident thermal neutrons and a TLD-600/700 pair unshielded, both with a thermal neutron shield between the TLDs and the reflecting body. These designs were studied primarily in an effort to reduce the dependence of a typical albedo dosimeter response on the separation distance from the reflecting body. The data were reduced as previously reported¹¹ i.e., a comparison of the ratio of incident-to-albedo neutron response (D₀/D₀) with the sum of their response in apparent R per rem (Σ (D₀ or D₀) R/rem). A summary of that work is plotted in Fig. 6 along with a similar analysis of the modified Hankins badge.

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**Fig. 7.** Four albedo badge designs calibrated with a Cf source in various thicknesses of hydrogen moderation.
References