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Tissue Equivalent Materials

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28

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POLYURETHANE AS A BASE FOR A FAMILY OF TISSUE EQUIVALENT MATERIALS

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212

INTRODUCTION

Two very important parameters must be considered when selecting and using tissue equivalent materials. First of all, the tissue being simulated must be specified. The human body contains a range of tissues and tissue compositions from the low density volume of the lung with a specific gravity of about 0.3 to solid bone with densities more than six times greater. When the tissue is not specified, reference is usually being made to lean muscle which has been specified in a formal way by the ICRP (1). The second parameter that must be carefully specified is the type of radiation being used and the interaction parameter in question. Material that is "tissue equivalent" for the linear transmission of x-rays may be a poor simulant for neutron dosimetry applications. In the first case, the density, effective atomic number, and photon attenuation coefficients are important parameters, while for neutron interactions, the elemental composition, with particular attention to hydrogen and nitrogen may be important. In the case of high energy neutrons, the relative carbon and oxygen compositions of the simulating material become significant.

It is also important to remember that human tissue is not necessarily uniform or homogenous. Layers or striations of fat through muscle, for example, lend a great deal of variability from one tissue volume to the next. In addition, differences between people make precise definition of tissue composition nearly impossible.

Over the years, a number of formulations have been used to simulate the tissue of most general interest - lean muscle. These include, but are not limited to: Temex, a depolymerized rubber (2); Mix-D, a paraffin polyethylene based material (3); rando muscle equivalent material, an epoxy based simulant and Shonka A-150 muscle equivalent plastic (4) formulated for dosimetry applications with an emphasis on neutron interactions. Most of these formulations have been selected to simulate only one tissue. However, White has adopted the use of epoxy formulations as a basis for accurate simulation of a wide variety of human tissues including lung (5).

In the last few years we have been involved in fabrication of a realistic torso phantom for calibration of counters used to measure internal depositions of transuranic isotopes. Since these isotopes are primarily measured via low energy L X-rays, the important characteristic we needed to simulate was low energy photon (≥ 13 keV) attenuation. In addition, it was important to simulate not only muscle, but adipose, cartilage, bone, and lung to adequately represent the torso morphology adequately. For various reasons, including the need for ruggedness and flexibility in the finished torso and organs, none of the available simulations were fully satisfactory for our purpose.

POLYURETHANE

Our search for a plastic material that could be used as a basis for simulating the wide variety of tissues needed for our application, led us to the selection of polyurethane. Polyurethane has

a density in the range of 1.03 to 1.08 g cm⁻³, is flexible, easily molded in a variety of shapes. The material we use has a composition of 9.4% hydrogen, 64.2% carbon, 3.1% nitrogen and 23.3% oxygen, however a variety of other suitable commercial polyurethanes are available. The casting procedures used for polyurethane make it relatively easy to add a wide variety of materials that can be used to adjust the density and effective atomic number to simulate the tissues in question. Finally, special polyurethane formulations are available that can be used to make foamed shapes with densities in the range of 0.2 to 0.3 g · cm⁻³ - suitable for mock lungs.

Like epoxy, polyurethane is fabricated from two basic components. Our procedure involves including additives such as calcium carbonate, urea, polyethylene, and acrylic microballoons into one component of the polyurethane before casting. In low concentrations (a few per cent) of these materials, only vigorous mixing is needed to achieve a homogenous casting. In high concentrations, such as that needed for rib bone or a general purpose muscle simulation, we find that availability of a roll or ball mill, similar to those used for making paint are important to achieve the necessary homogeneity. Once the proper additives have been mixed in component A of the polyurethane, the formulation is completed by combining with component B and a trace quantity of catalyst used to help the polyurethane set properly. This mixture should then be evacuated in a large container to eliminate trapped air bubbles following the mixing process. After evacuation, the mixture is poured into the molds that have been prepared for the desired shapes, and the tissue equivalent casting is left to cure and harden for a period of about 24 hours.

One requirement of the phantom project was that we be able to incorporate transuranic isotopes uniformly through the lungs and other organs to simulate internal deposition for calibration of whole body counters. We can do this easily with polyurethane by dissolving the radionuclide in nitrate form, together with a small amount of lanthanum nitrate carrier, in acetone. This solution mixes well with the polyurethane before casting and results in highly uniform organ labelling.

SPECIFIC FORMULATIONS

During the last three years, we have developed polyurethane based formulations that are primarily designed to represent the low energy photon transmission properties of muscle, adipose, cartilage, bone and lung. The data and criteria of Newton and White (6) have provided guidance in developing a formulation of many of our materials. Our original muscle equivalent formulation was actually chosen to simulate the transmission of 17.2 kV x-rays from Pu through water rather than muscle. The differences between tissue and muscle are not great for our purpose, and water is a readily available, precise standard for attenuation. It is this formulation (LLLM1), that has been used in the phantoms that we have fabricated so far.

Recently, we have used criterion of Newton and White to refine formulations of some of the more important tissues for future applications. In particular, we have extended our formulation inventory to include a more accurate simulant of the ICRP muscle, with closer attention to reproducing the elemental concentrations of hydrogen and nitrogen that are important for neutron dosimetry applications (Table 1). It is possible using this formulation to cast a solid sphere of muscle equivalent material that would be useful as a physical representation of the ICRP-30 cm spherical phantom for calibration purposes.

Table 1. Polyurethane Tissue Equivalent Formulations

LLLM1	95.7% Polyurethane, 4.3% CaCO_3
LLLM2	66.4% Polyurethane, 25.0% polyethylene, 5.6% CaCO_3 , 3.0% urea
LLLA1	99.4% Polyurethane, 0.6% acrylic micro-balloons
LLLR1	67.0% Polyurethane, 33.0% CaCO_3
LLLL1	96.2% Polyurethane, 3.8% CaCO_3

Table 2 shows a comparison of tissues and simulants for dosimetry applications. The electron density - N_0 , and the average atomic number - $\bar{Z}$ have been calculated from the formulas of Spiers (7).

$$N_0 = 6.023 \cdot 10^{23} \sum \frac{P_i Z_i}{A_i} \quad \text{and} \quad \bar{Z} = \left[\frac{6.023 \cdot 10^{23} \sum \frac{P_i Z_i^{3.94}}{A_i}}{N_0} \right]^{\frac{1}{2.94}}$$

Where P_i is the weight fraction of the i th element
 Z_i is the atomic number of the i th element
 and A_i is the atomic weight of the i th element.

Table 2. Calculated Radiation Interaction Related Properties of Tissues and Simulants

Material	Density $\text{g} \cdot \text{cm}^{-3}$	μ_{rat}		$\bar{Z}$	Neutron Kerma ^a (Ref 8)	
		17.2 keV cm^{-1}	10^{23} No - gm^{-1}		$10^{-10} \text{ rad} \cdot \text{cm}^2$ thermal	1.05 MeV
Muscle(1)	1.04	0.872	3.31	7.46	0.279	24.8
Temex(2)	1.01	0.677	3.27	7.07	0.00898	22.5
Mix-D(3)	0.97	0.726	3.40	6.95	0.00585	30.6
Rando Muscle	1.00	0.730	3.27	7.39	0.336	21.2
Shonka(8)	1.12	0.756	3.30	6.86	0.279	23.6
MS 20(5)	1.00	0.861	3.24	7.47	0.144	19.5
LLLM1	1.08	0.815	3.27	7.14	0.182	20.7
LLLM2	1.05	0.862	3.31	7.25	0.278	23.7
Adipose(1)	0.92	0.410	3.38	6.23	0.0687	27.9
AP6(5)	0.92	0.405	3.25	6.30	0.190	20.2
LLLA1	0.93	0.401	3.29	6.26	0.253	22.5
Rib Bone(6)	1.27	3.85	3.21	10.77	0.296	17.7
RB2(6)	1.26	3.88	3.20	10.77	0.242	15.8
LLLR1	1.33	3.96	3.20	10.67	0.169	15.9
Lung(1)	0.26	0.218	3.31	7.46	0.279	24.8
LN1(6)	0.26	0.222	DATA	NOT	AVAILABLE	
LLLL1	0.28	0.193	3.17	6.97	0.287	21.4

Newton and White (6) point out that the linear photo-electric attenuation coefficient - $\mu\tau$ - for low energy photons is a particularly important parameter in simulating tissues for x-ray applications. Therefore, we have included calculated values of $\mu\tau$ for the 17.2 keV uranium L X-ray from the decay of plutonium.

Neutron dosimetry applications and specification of the ICRP-30 cm phantom have generated a specific interest on our part in simulating the tissue compositions used for that application. In this case, not only photon attenuation but elemental composition is of importance. Table 2 also shows a comparison of the ICRP reference muscle with tissue simulants. It is important to note, that, although the A-150 plastic is not necessarily an adequate tissue simulation for low energy photon applications, it is still probably the best material available for use in ion chambers or other devices requiring a conducting material.

SUMMARY

We have used polyurethane as a base material for a wide variety of tissue simulating applications. The technique in fabrication is similar to that of epoxy, however, the end products are generally more flexible for use in applications where flexibility is valuable. The material can be fabricated with relatively small laboratory equipment. The use of polyurethane provides the dosimetrist with the capability of making specific, accurate, on-the-spot tissue equivalent formulations to meet situations which require immediate calibration and response.

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