Application of advanced composite materials in the creation of reference volume sources of radionuclides activity

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ABSTRACT

STC “RADEK have developed a technology of composite materials manufacturing for the manufacture references volume samples. The obtained materials are homogeneous, chemically inert and stable in normal operating conditions, are not affected by oxidation and are not hygroscopic. The introduction of reference radionuclides solutions in the material, which is provided by manufacturing technology, allows to obtain a highly stable activity volume sources with precisely specified metrological characteristics. At the present moment, in STC “RADEK designed and manufactured new radiodosimetric anthropomorphic organotropic phantom of human body using this composite materials.

KEY WORDS

Composite materials, reference materials, whole body phantoms, WBC, tissue equivalence.

INTRODUCTION

Modern measuring instruments used in the field of the radio-ecological monitoring apply spectrometric and radiometric analysis method. Spectrometric method provides, in addition to the measurements of activity the identification of radionuclides, present in the measured object.

Spectrometric method of analysis is a relative method, so it is of importance to increase the manufacturing accuracy of the reference volumetric samples of activity (RVS) used to calibrate the instruments, as one of the main contributions to the uncertainty of radionuclide activity measurements is the uncertainty of the characteristics of the calibration samples.

While making the volumetric samples of activity it is necessary to ensure their maximum possible concordance with the measured sample by the geometric and physical-chemical characteristics such as shape, size, density, mass absorption coefficient of X-ray and gamma radiation, the distribution of activity.

STC "RADEK" in cooperation with the FSUE NIIPMM (St. Petersburg) has developed the manufacturing technology of composite materials with a given density in the range 0.1 g/cm3 to 3.0 g/cm3 (with the manufacturing accuracy of 1.5-3% in density) and the dependence of the mass absorption coefficient on energy in the operating range 10 to 3000 keV, at a total deviation not exceeding 3%. The total deviation has been determined by the following formula:

$$u = \frac{\sum_{i=1}^{n} \left| \mu_i - \overline{\mu_i} \right| / \mu_i}{n} \cdot 100\% \qquad (1)$$

μ_i - measured value of the mass absorption coefficient for a particular type of material;

$\overline{\mu_i}$ - table value of the mass absorption coefficient for the equivalent material [1];

n - number of measurements of the mass absorption coefficient, for different energies of gamma rays.

The manufacturing technology provides the introduction of the standard solutions of radionuclides, fixed in the matrix carrier, to the material, which enables highly stable volumetric samples of activity (VSA) with the exactly specified metrological characteristics to be obtained. Typical distribution of activity is uniform in volume.

The specific feature of the technology is the possibility of producing stable and hygienic simulators of the natural and man-made objects, including the simulators of biological tissues.

PROPERTIES OF MATERIALS

The materials obtained have the following positive characteristics:

- tissue equivalence to biological tissues;
- homogeneity of the components distribution, which is provided by using the developed technology and methods of control;
- hygienic in comparison with the samples of biological tissues;
- chemical inertness and stability under normal operating conditions;
- the possibility of producing models by molding;
- the possibility of introduction of radionuclides of the required activity.

THE CRITERIA OF TISSUE EQUIVALENCE

The main types of interaction of gamma radiation with the substances:

(1) Photoelectric absorption (photo-effect).

(2) Scattering of photons on free electrons (Compton scattering).

(3) Production of electron-positron pairs.

The probability of absorption of X-ray and gamma radiation is determined by the sum of interaction cross sections for the photo-effect, Compton scattering and the effect of pair production ($\mu = \tau + \sigma + \chi$). Within the energy range up to 3 MeV the dependence of μ on the atomic number effectiveness Z_{eff} changes: from the $\mu = f(Z^4_{eff})$ function - for the photo-effect to the $\mu = f(Z^1_{eff})$ - for the pair production. The cross section for Compton scattering does not depend on Z_{eff}.

The equivalence of attenuation of the X-ray and gamma radiation for the designed material and biological tissue can be reached only by fitting of the absorption coefficient μ. This fitting of the μ valuse must be performed for two energies of photons: at E≤ 30 keV (the range of the photo-effect) and at E ≥ 60 keV (the range of the Compton scattering).The value Z_{eff} usually used for assessment of tissue equivalence is various in the wide range of energies of photon radiation [12].

The calculation of the composite materials composition was carried out for radiation energies of 15 keV and 60 keV, the tabulated value of mass absorption coefficient of the chemical elements are taken from [1].

Fig.1 shows dependences of linear absorption coefficients (for clarity) on energy for the materials: bone biological tissue (BBT), soft biological tissue (SBT), lungs biological tissue (LBT), Polyethylene.

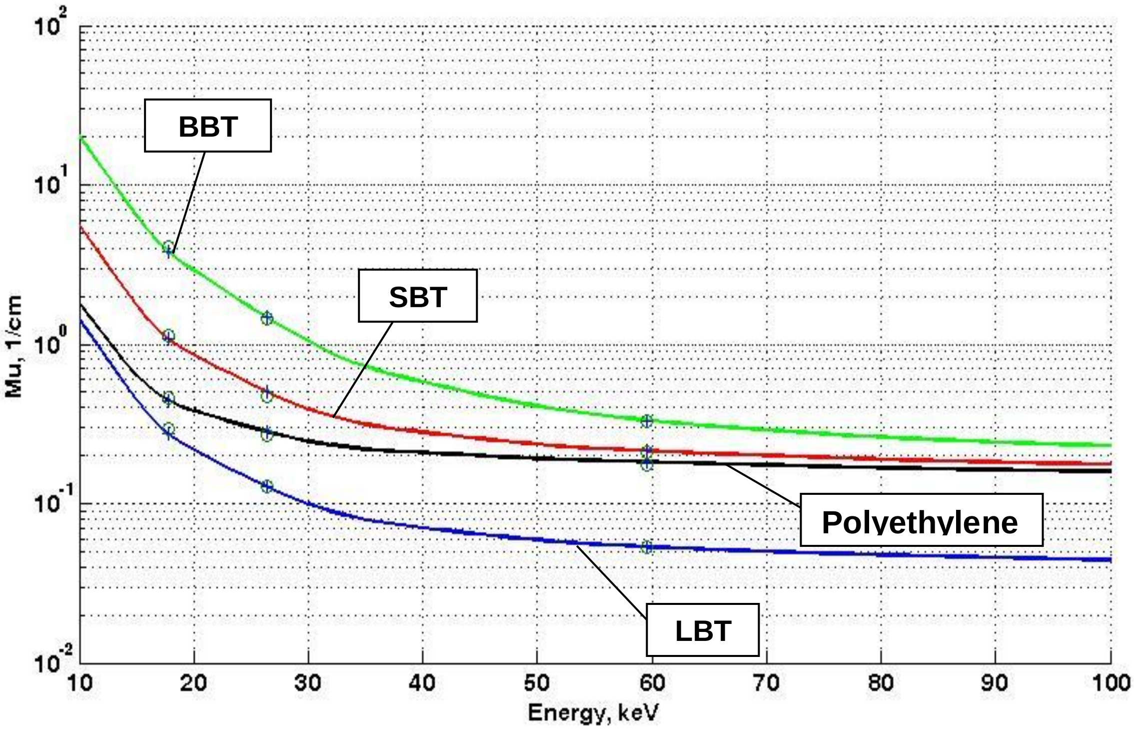

Fig.1 Dependence of linear absorption coefficient on radiation energy

The approximation of the tabulated values of mass absorption coefficients [1] has been performed by the cubic splines method with the subsequent account of material density for calculating linear absorption coefficients.

In Fig.1 the experimental values of linear absorption coefficients obtained while controlling the quality (see " Quality Control of Materials") are marked with circles.

MODELING OF BIOLOGICAL OBJECTS. THE HUMAN BODY PHANTOM

Of special importance among the volumetric samples of activity, made from composite materials, are phantoms of the human body, its parts and organs, designed for the calibration of the whole body spectrometers (WBC), as well as for the dosimetric studies.

At present, STC "RADEK", on the request of the Radiation and Nuclear Safety Authority in Finland (STUK), designed and manufactured a new radiodosimetric anthropomorphic organotropnic human body phantom ARDF-09T, shaped as an assembled and dissembled model of an adult man, aged 18-20 years. (Fig.2). The body parameters of the phantom are in keeping with the ICRP recommendation [3] and the corresponding picture in a human anatomy atlas[9].

The phantom contains a full set of the skeleton bones models, organs models and investing tissues models (Fig.3), which are mounted on spot. Models are made of the plastic materials simulating biological tissues, adequate to human tissues as far as the interaction with ionizing radiation is concerned.

Fig.2 Exterior view of the phantom ARDF-09T trunk

Fig.3 Set of bones and organs from the phantom ARDF-09T

The designing principle of tissue equivalent materials - simulators of biological tissues is borrowed by the developers from the recommendations of the International Committee on Radiation Units (ICRU) [2].

The composition of the modeled biological tissues was adopted according to the recommendations of ICRU [3,5]. As the modeled skeleton tissue the averaged bone tissue consisting of: bone (53,7%), cartilage (10,7%), red bone marrow (11,4%), yellow bone marrow (24,2%) was assumed at the average density p=1,3 g/sm^3. For the soft biological tissue the composition of skeleton muscles was assumed at the density p=1,04 g/sm^3 . As the modeled lungs tissue the averaged lungs tissue was assumed at the density p=0,26 g/sm^3.

The composition of the materials used for manufacturing the background phantom ARDF-09T, is presented in Table 1.

Table 1

Source components	Weight fraction of the component in the material, %		
	BBT	SBT	LBT
Binders:			
- epoxy resin ED-20	36,50	29,36	29,04
- hardener PO-300	21,90	17,61	17,44
- plasticizer DBF	7,29	5,87	5,80
Fillers:			
- chromium oxide	2,21	11,18	2,64
- calcium carbonate	-	3,68	-
- microspheres (0.138 g/cm^3)	2,10	0,24	45,08
- tapiokocic starch	30,00	32,06	-

The composition of the materials indicated in Table 1, provides the tissue equivalence of the plastic material - simulators to bone, soft and lungs biological tissues within the range not exceeding 3% by the total deviation for the energy interval from 17 to 60 keV, which in accordance with the ICRU recommendations is sufficient for the radiometric and dosimetric phantoms.

The phantom is used for two purposes. The background phantom not containing the radionuclide organs models, is intended for measuring the absorbed doses of X-ray, bremsstrahlung and gamma radiation in organs and tissues of the phantom from external ionizing radiation sources using thermoluminescent detectors (TLD) installed in the special pits. The phantom containing the radionuclide organs models is used for calibrating whole body spectrometers to measure the incorporated radionuclides.

The list of the phantom components is presented in Table 2.

Table 2

Component	Quantity
Head phantom consists of 5 detachable components: - frontal bone with investing tissue; - parietal bone with investing tissue, left part; - parietal bone with investing tissue, right part; - base of skull with facial bones, including face investing tissue; - brain (cranial contents).	1
Neck phantom consists of 5 detachable components: - throat; - cervical spine; - thyroid;	1

- front of neck; - back of neck.	
Body phantoms models thoracic, lumbar, pelvic-abdominal body parts and consists of 29 detachable components: - shoulder-blade, left; - shoulder-blade, right; - collarbone, left; - collarbone, right; - spine, thoracic; - connective tissue covering spine, right part; - connective tissue covering spine, right part; - spine, lumbar part; - pelvic bone, left; - pelvic bone, right; - sacrum; - bone marrow; - lung, left; - lung, right; - thymus; - heart; - liver; - stomach; - spleen; - pidney, left; - pidney, right; - investing tissue of chest with front of ribs; - investing tissue of abdomen; - investing tissue of back with back of rib; - investing tissue of lumbus with buttocks; - skeleton (total organs tissue of pelvic-abdominal body part together with total tissue of pancreas); - « lighthouse », central body (total tissue of esophagus, trachea, aorta, vena cava, and other tissues of chest);	1
Hand and arm phantom consists of 7 detachable components - shoulder bone - forearm bones - hand bones with investing tissue - investing tissue of shoulder bone (front part) - investing tissue of shoulder bone (back part) - investing tissue of forearm bones (front) - investing tissue of forearm bones (back)	2
Legs and feet phantom consists of 8 detachable components: - thigh-bone - patella (kneecap) with investing tissue - shin bones - feet bones with investing tissue - investing tissue of thigh-bone (front) - investing tissue of thigh-bone (back) - investing tissue of shin bones (front) - investing tissue of shin bones (back)	2

A radiometric phantom set contains interchangeable sets of the organs models containing radionuclides of the certain activity. The approximate composition of models with the incorporated activity is presented in Tables 3-5.

Table 3

Radionuclide	Bones models (quantity)					
	head	neck	body	hand and arms	feet and legs	total
Strontium-90	4	1	11	6	8	30

Table 4

Radionuclide	Organs models (quantity)					
	lungs	kidneys	liver	heart	thyroid	total
Cobalt-57	2	-	-	-	-	2
Cobalt-60	2	-	-	-	-	2
Barium-133	-	-	-	-	1	1
Europium-152	2	2	1	1	-	6
Plutonium-238	2	2	1	1	-	6
Americium-241	2	2	1	1	-	6

Table 5

Radionuclide	Bones models (quantity)						
	frontal bone	parietal bone	patella	thigh-bone	shin	chest	total
Europium-152	1	2	2	2	2	2	11
Lead-210	1	2	2	2	2	-	9
Radium-226	1	2	2	2	2	-	9
Plutonium-238	-	-	-	-	-	2	2
Americium-241	1	2	2	2	2	2	11
Uranus natural	1	2	2	2	2	-	9

The admissible values range of the specific activity of radionuclides in the materials - simulators of biological tissues using for manufacturing the radionuclide organs models is not normalized. The list of the manufactured radionuclide organs and the range of admissible values of the specific activity of the radionuclides contained are provided by the user requirement. The specific activity of radionuclides in the materials - simulators of biological tissues, as a metrological characteristics is determined in the process of the metrological certification of the phantom.

Depending on the type of the whole body spectrometers, measurement geometry and the incorporated radionuclide the specific activity value contained in the organs models, can be within the range from 2 to 10^6 Bq / g (when establishing the admissible range of specific activity it is necessary to proceed from the condition that the input statistical intensity of counts while calibrating the spectrometer using the phantom, should not exceed $10^3 c^{-1}$).

QUALITY CONTROL OF MATERIALS

Quality of the prepared materials was controlled by comparing the density values and mass absorption coefficient of photon radiation, measured directly on the materials samples with the admissible normative values (see tables 6 and 7).

The density of the materials - simulators of the biological tissue was determined as the ratio of sample mass to its volume. The mass was found by direct weighing and the volume was determined by the displaced volume of the fluid in accordance with SSS 15139-69 [9]. This method provides the density measurement accuracy up to 0.5% by volume measurement accuracy of 0.3% m and the mass measurement accuracy of 0.2%.

The mass absorption coefficient of photon radiation in the materials - simulators of biological tissues was determined by performing the joined measurements:

- linear absorption coefficient of photon radiation in the materials under test on the energy of the radiation of Am-241: 17.74 keV, 26.34 keV, 59.54 keV. Measurements were performed in narrow beam geometry.
- samples density of the materials under test according to SSS 15139-69[9].

The error of the method for determining the mass absorption coefficient doesn't exceed 4%.

Table 6

Material type	Results of measurements of density in the manufactured materials, g/sm^3		Deviation, %
	Normal	Obtained	
BBT	1,30	1,33	2,3
SBT	1,04	1,02	1,9
LBT	0,26	0,27	3,8

Table 7

Material type	Results of measurements of mass absorption coefficient of photon radiation, sm^2/g for energy						Total deviation, %
	17,74 keV		26,34 keV		59,54 keV		
	Normal	Obtained	Normal	Obtained	Normal	Obtained	
BBT	3,060	3,116	1,120	1,112	0,256	0,253	1,23
SBT	1,090	1,085	0,470	0,458	0,206	0,203	1,48
LBT	1,110	1,132	0,480	0,489	0,206	0,203	1,77

CONCLUSION

The anthropomorphic human body phantoms make it possible to execute the calibration of the whole body spectrometer (WBC) of the expert class.

So, at the present time, STC "RADEK" (St. Petersburg, Russia), has carried out the calibration of the whole body spectrometers of the SEG-10P-01 type to measure:

- ^{131}I in thyroid;
- ^{137}Cs, ^{134}Cs in whole body;
- ^{60}Co in lungs;

It should be noted that modern means of computer simulation, enabling theoretical calculation of the registration efficiency dependence of ionizing radiation on the objects of simple forms to be carried out, have confirmed the adequacy of the test objects at the investigating stage.

While monitoring the radiation situation in the observation zone of the emergency objects of the Nuclear Industry it is necessary to manufacture and utilize the phantoms with the certain content of transuranic elements, as a reference sample of activity, for calibrating the whole body spectrometers. This necessity is due to specific danger of transuranic elements inhalation, including plutonium, for a human.

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