

## CHECKING A MONTE CARLO UTILITY FOR WHOLE BODY COUNTING DURING *IN VIVO* EXPERIMENT

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### ABSTRACT

A utility for Monte Carlo application for whole body spectrometry of low-energy  $\gamma$ -rays emitted by incorporated radionuclides has been recently developed. The technique implies a graphical user interface for automatic creation of input data files for MCNP calculation and graphical analysis of calculation results as well. The patient's anatomy is described in terms of voxels retrieved on the base of x-ray or magnetic resonance computer tomography images. The new method for whole body spectrometry calibration, including tomography image processing and Monte Carlo calculations, was checked in a quasi-*in vivo* experiment on large-sized animals (young pigs weighing approximately 35-40 kg). During the experiment, the reference activity of  $^{241}\text{Am}$  was administered (via injection of a radioactive solution and via implantation of plastic capsules containing the radioactive material as well) into the lungs of specially operated animals. The pigs were measured with pure germanium low-energy  $\gamma$ -spectrometers Canberra Industries, Inc. The images of animals were obtained using the Toshiba Aquilion x-ray tomography machine. On the base of these tomograms, MCNP4c2 calculations in voxel phantom geometry were done to obtain the pulse-height-spectra of the Canberra Industries whole body counters. The comparison of calculation and experimental results is discussed for different methods of activity administration into the lungs (injection vs. capsulation).

*Key Words:* whole body counting; animal experiment; professional irradiation; MCNP; voxel phantom

### 1 INTRODUCTION

Monitoring of internal irradiation of nuclear industry personnel involves whole body counting spectrometry of incorporated radionuclides. During measurements of actinide (uranium, plutonium, americium etc.) body burdens, some complications occur. These complications are

related to low energy of  $\gamma$ -rays emitted by the majority of these radionuclides, which are distributed at different depths inside the body, whereas the measurements are conducted over the body surface. The anthropometrical differences of an individual patient significantly affect the measurement geometry and followed results.

The general approach, which is tested in the present study, implies individual numerical calibration of whole body counting of incorporated low energy  $\gamma$ -emitters. To simulate the measurement conditions adequately, radiation transport is calculated with Monte Carlo method (MCNP code [1] is used) in the geometry, which represents the individual anatomy. The patient's anthropometrics and anatomy are obtained via x-ray computer tomography (CT) or magnetic resonance imaging (MRI). The MCNP input data file is automatically created with the software  $\text{\textcircled{E}DIPE}^*$  (formerly named *Anthropo*), which has been recently developed at Institut de Radioprotection et de Sûreté Nucléaire (IRSN; Fontenay-aux-Roses, France) [2].  $\text{\textcircled{E}DIPE}$  describes the individual anatomy via rectangular boxes of small size (voxels).

Practical application of “voxel phantom” technique for calibration of whole body counters is impossible without the comparison of measurement versus calculation results. Previous works [2, 3, 4, 5] have reported on such a comparison for measurements of reference plastic phantoms, arbitrary biological samples and a patient's finger. To perform a thorough experimental check on human-size animals, the partnership project under the egide of International Science and Technology Center (ISTC) has been established. The project involves State Research Center — Institute of Biophysics (IBPh; Moscow, Russia) and IRSN. Transfer of experimental data obtained using whole body counters at IBPh to the analogous devices at IRSN requires careful experimental comparison of Russian and French equipment, including metrology specifications of phantoms and radiation sources. Such a compliance establishment between whole body counting equipment at IBPh and IRSN has been performed previously [5].

The present paper reports on a test of whole body counting technique with computer-assisted calibration in the experiment on large-size animals (pigs), which were used as phantoms for measurements of incorporated actinides.

## 2 ELABORATION OF THE EXPERIMENTAL PROTOCOL

The project presumes the use of  $^{241}\text{Am}$  for measurement with whole body counting equipment. This radionuclide is usually incorporated together with other actinides inside the bodies of nuclear fuel cycle employees. The relatively high (59.54 keV) energy of the major portion of  $\gamma$ -radiation emitted by  $^{241}\text{Am}$  facilitates the detection of radiation.

First studies of pharmaceutical kinetics of  $^{241}\text{Am}$  on experimental animals after the inhalation intake were conducted in 1967-1968 [6, 7, 8]. Various biological effects of incorporated  $^{241}\text{Am}$  are often studied on rats; the use of dogs, pigs, and monkeys is less frequent. However, in the present experiment we preferred to involve pigs, which are the closest to humans if compared to other animal species regarding body mass, basic metabolism, biokinetic parameters of transuranium nuclides and reaction on radiation exposure (see Table I, according to [9]).

Summing up the data [12, 13, 14, 15] on  $^{241}\text{Am}$  behavior inside the human body in case of

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\* $\text{\textcircled{E}DIPE}$  is the abbreviation of a French phrase, “Outil d’Evaluation de la Dose Interne PErsonnalis e”

**Table I: Comparison of some general characteristics of different animal species versus human (radiation exposure reactions, according to [9])**

Species	Body mass, kg	Average life span, years	Basic metabolism, Cal/(kg × day)	Radiation exposure reaction					
				LD <sub>50/30-60</sub> , Gy		Half-recovery period, days	Threshold dose rate for behavior change, μGy/s	Dose rate effect in 0.01-1.00 Gy/min range	Day of maximal leukopenia
				Data [10]	Data [11]				
Mouse	n/a	n/a	n/a	9.41	5.28	1.6-7.4	n/a	n/a	n/a
Rat	0.18-0.22	4.0	100	9.36	5.88	4.9-8.5	120	Increased	8.0
Hamster	0.10-0.12	n/a	n/a	9.35	n/a	6.1	n/a	n/a	8.0
Guinea pig	0.3-0.5	5.0	85	2.55	3.55	1.2; 27.0	11	Unchanged	13.0
Rabbit	2.5-3.5	8.0	44.5	8.89	5.27	9.5; 27.0	n/a	Increased	n/a
Monkey	2.5-3.5	10	44.5	6.23	2.50	4.8	n/a	Unchanged	15.0
Dog	10-25	10	36.0	3.19	2.50	7.0-14; 16.9	n/a	Increased	17.0
Pig	n/a	n/a	18.0	3.99	n/a	3.0; 20-28	n/a	Increased	18.0
Sheep	45	n/a	26.0	2.51	3.09	23.0	n/a	Increased	18.0
Goat	36	n/a	22.0	3.31	n/a	60.0	n/a	n/a	n/a
Donkey	n/a	25.0	n/a	3.76	n/a	60.0	n/a	n/a	20.0-23.0
Cow	500	n/a	14.0	5.40	n/a	n/a	n/a	n/a	n/a
Human	65-70	70	24.0	4.00	n/a	20.0-28.0	n/a	n/a	23.0-30.0

different inhalation intake patterns, one can state that:

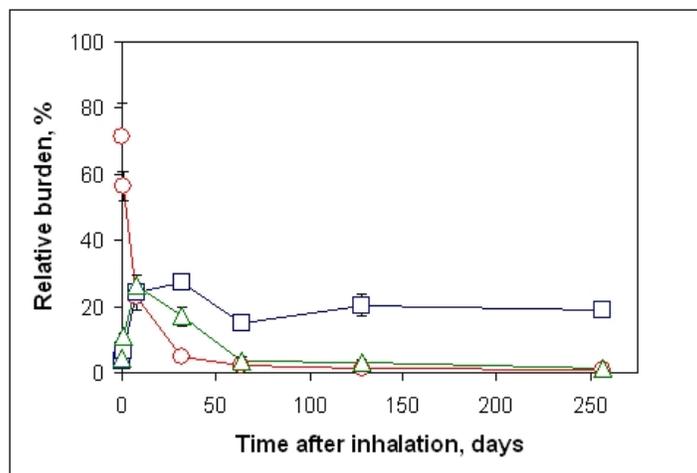
- some compounds are specific to rapid transfer (within several hours) of <sup>241</sup>Am from lungs to the blood flow;
- a portion of radioactivity deposited in lungs can be removed with half-time of several weeks;
- several months after <sup>241</sup>Am inhalation, it is found in liver, lungs and skeleton;
- 6-7 years after the inhalation, the major part of radionuclide is detected in skeleton.

As to animals, the information on <sup>241</sup>Am metabolism is absent for pigs and limited for dogs [16, 17]. However, the dog data for <sup>241</sup>Am soluble salts dynamics in different organs and tissues after single inhalation intake are similar to the human data (see Fig. 1).

Thus, maximal <sup>241</sup>Am quantity is contained in lungs during first days after the inhalation. However, the application of inhalation administration in the present experiment is not justified due to the following reasons: inevitable non-removable external contamination (expectoration, sneezing, superficial radionuclide sedimentation in the administration compartment), and complications related to preparation of the reference aerosol of necessary concentration.

The application of diet administration results to insignificant radionuclide burden in lungs if compared to other organs (gastro-intestinal tract, liver, bony tissue).

The direct radionuclide injection in lungs is complicated by possible lung collapse. However, the special surgical manipulation (see Section 3.2) can prevent this disadvantage and provide the necessary effect of known lung burden and simultaneous absence of radionuclide in other organs or in the body surface of the animal. Project participants proposed the injection administration of the activity in lungs to get the adequate simulation of the radionuclide intake to the human lungs



**Figure 1: Relative (% of initial lung burden)  $^{241}\text{Am}$  nitrate burdens in different organs of dogs (red  $\circ$  — lungs, green  $\triangle$  — liver, blue  $\square$  — skeleton) at different time periods after single inhalation intake. Initial lung burden was calculated via summing up  $^{241}\text{Am}$  activity found in all organs, urine and feces (excluding feces activity at week 1).**

in case of the occupational inhalation contact with actinides. Moreover, the injection administration to animal lungs is pretty suitable for followed whole body counting.

The experimental data for the first animal point to the drainage of radioactive solution along blood vessels and bronchi, as well as to the leakage of the activity outside of lungs (see more details in Section 4.1). This phenomenon produced inhomogeneous activity distribution inside the lungs as well as presence of activity outside the lungs. As a result, the accurate computational reconstruction of the measurement was hampered. To circumvent this obstacle, insertion of capsules with  $^{241}\text{Am}$  preparation instead of injection was used for two last pigs.

### 3 DESCRIPTION OF EXPERIMENTAL WORKS

Four pigs (35-40 kg body mass, 3.5-4 months age) were used for the experiment. The animals were purchased at a farm in Moscow suburb area.

#### 3.1 Anesthesia and Tomography

Before the x-ray CT scan and surgical manipulations, the animals were applied by anesthesia according to [18, 19, 20, 21]:

1. Premedication before introductory anesthesia:
  - (a) Atropine (Atropini sulfas) — single dosage of 2 mg (2.0 mL of 0.1% solution) i.v. in the ear edge vein.
  - (b) Dormicum (Midazolam) — single dosage of 3 mg i.v. in the ear edge vein.

2. Introductory (inductive) anesthesia — 20 min before basic anesthesia:

- (a) Sodium thiopental (Thiopentalum natrium) — 1000 mg dosage (25 mg/kg, 20 mL of 5% water solution) i.m.

3. Basic anesthesia:

- (a) Sodium thiopental (Thiopentalum natrium) — 1500 mg dosage (40 mg/kg, 20 mL of 5% water solution) i.m.
- (b) Sodium oxybutirate (Natrii oxibutiras), sodium salt of gamma-oxy-oil acid (GOOA) — 4000 mg dosage (100 mg/kg, 20 mL of 5% water solution) i.m.

Anesthesia pigs were fixed in the plastic container and transported to the CT department of Clinical Hospital No. 6 of Federal Medico-Biological Agency (Moscow, Russia), where CT imaging was conducted.

### 3.2 Surgery and Reference Activity Administration

After the CT imaging, the pigs were delivered to the animal house of IBPh, where surgery was done before radioactivity administration.

The major purpose of the pre-administration preparation was the prevention of the postmortem blood loss and lung collapse. Following measures were taken:

- The pigs applied with anesthesia (see Section 3.1) have got the skin dissection at trachea (above shield cartilage); the dissection length was below 7 cm, which provides minimal blood loss and necessary “freedom” for followed manipulations;
- With blunt instruments (scalpel handle, forceps) the subcutaneous tissue and muscles were moved without vascular injury (so-called “blunt” passage) with careful liberation of trachea in the whole perimeter;
- On the inspiration height, the trachea lumen was completely compressed with branches of the length exceeding the respiratory pipe diameter.

In the following day, the rib knife was used to dissect skin and subcutaneous tissues at sternum middle to the border line of chest-abdomen cavity (diaphragm projection). Two other skin cuts were perpendicular to the first one and directed to the vertebral column; large section knife was used to separate cutaneous-muscular flap from the chest (on the left) and at the sternum (on the right) down to the rib cartilage. Rib cartilage was dissected to separate sternum. Using Liston forceps, ribs were intersected on both sides at 4-5 cm distance from column; rib muscles were intact. The entrance to all lung compartments was open, which is essential for radionuclide administration homogeneity.

Naked lungs of pigs No. 1-2 were administered with  $^{241}\text{Am}$  nitrate, which solution was prepared from quality assured substance. The solution of pH-1 acidity was sampled by the batcher micropipette, and 200  $\mu\text{L}$  of the radionuclide solution was placed to the single-used syringe with needle. The stability of the batcher was previously checked by measurement of 10 samples using the scintillator spectrometer Gamma Track manufactured by Delta Medica.

Average  $^{241}\text{Am}$  activity per one injection was  $(1.03 \pm 0.05)$  kBq, the specific activity of the solution was 4.9 kBq/mL. To indicate the injection points, the same syringe (without needle extraction from the tissue) was used to administer 50  $\mu\text{L}$  of blue paint (SERVA), which amount was measured by batch micropipette. The right lung of the pig No. 1 had 14 homogeneously distributed points and left lung of the same pig had 13 (27 points in total). Each lung of the pig No. 2 had 27 points (54 points in total).

As far as mentioned in Section 2, to prevent activity drainage and leakage, as well as to ascertain the  $^{241}\text{Am}$  source localization for mathematical simulation, we administered the activity into the lungs of pigs No. 3-4 via alternate method. The paper pieces with dried  $^{241}\text{Am}$  nitrate solution have been enclosed into plastic capsules with length of about 1 cm and diameter of about 2-3 mm. To fix the position of the capsules inside the lung, small hooks made from thin copper wire were attached to the capsules. The capsules were inserted into the uniformly distributed cuts in the lung tissue made with a scalpel. The average activity of one capsule measured by the Gamma Track spectrometer was equal to 2155 Bq (with minimal value of 2251 Bq and maximal value of 2102 Bq). 27 capsules were inserted into each lung of the pig No. 3 (54 capsules in total). The right lung of the pig No. 4 had 14 capsules inserted and the left lung of the same pig had 13 (27 capsules in total).

After radionuclide administration, the chest wholeness was recovered (sternum was fixed in its place) and skin was sewed. Such a manner of animal preparation provides preservation of natural topography of organs and superficial tissues of the chest.

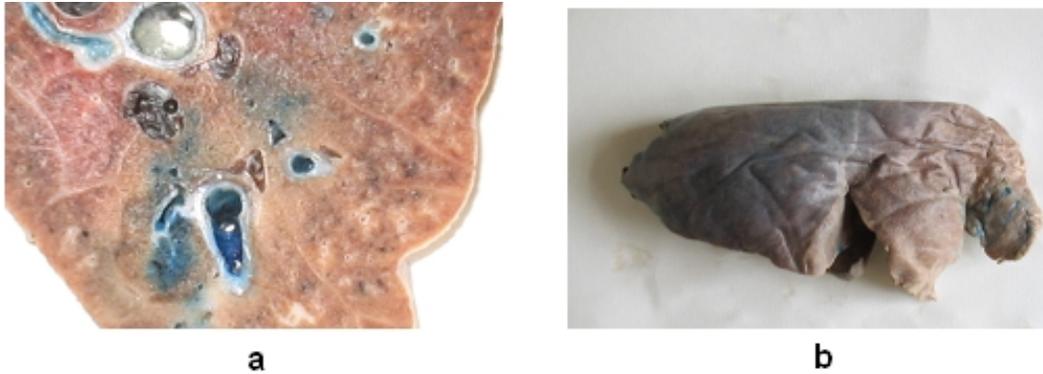
### **3.3 Whole Body Counting, Postmortem Tomography, Autopsy, Organ Slicing and Waste Utilization**

After the surgery, the animals were transported to the whole body counting laboratory of IBPh, where two detectors (manufactured by Canberra Industries) were used to measure  $^{241}\text{Am}$   $\gamma$ -radiation. For the animal No. 1, measurements were done with detectors placed in front of the upper and lower parts of the left and right lungs. Animals No. 2-4 were measured with detectors placed in front of the upper part of each lung only.

To ascertain the location of capsules, the animals No. 3-4 were scanned for the second time (postmortem) using the Toshiba Aquilion CT machine.

After whole body counting and postmortem tomography, the chest was dissected again, trachea was bandaged and lungs extracted. Lungs of pigs No. 1-2 were placed to 10% solution of neutral formalin for fixation. Lungs of pigs No. 3-4 were utilized after the removal of the capsules. The fixed right lung of the pig No. 1 was sliced into 2-3 mm thickness slices (41 slices in total). The left lung of the pig No. 1, and both lungs of the pig No. 2 are archived.

Other animal organs, instruments (syringes, pig container etc.) contaminated with  $^{241}\text{Am}$  were utilized by Radon SPA Company with followed deposition in the radioactivity depository.



**Figure 2: Cross-section (panel “a”) and general view (panel “b”) of the right lung. SERVA paint marks demonstrate the activity drainage inside blood vessels and bronchi as well as the possible leakage outside the lung via syringe needle punctures in the lung tissue (panel “b” on the right).**

## 4 RESULTS

### 4.1 Postmortem Activity Measurement in Lungs

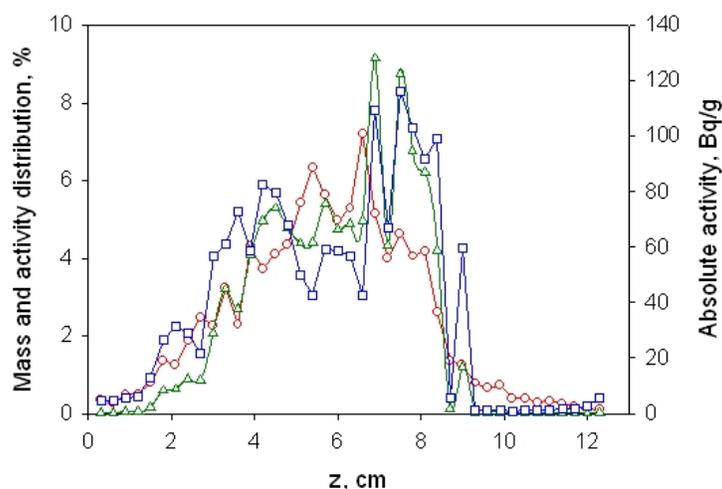
To assess the spatial distribution of the activity injected into the lungs, the right lung slices of the pig No. 1 were examined by visual observation of SERVA paint marks and by measurement using the Gamma Track spectrometer. Visual observation (see Fig. 2) shows activity drainage along blood vessels and bronchi (panel “a”), as well as leakage outside the lung through punctures in the lung tissue (panel “b”).

$^{241}\text{Am}$  activity leakage is confirmed by lung slice radiometry, providing the total activity of 9.5 kBq, which is about 30% less than administered activity (14 kBq); see also Table II. The analysis of spatial activity distribution (see Fig. 3) certifies that major portion of the activity is concentrated in the central part of the lung. The leakage has occurred mostly in the small-size sections in the upper and lower parts of the lung.

In contrast to the right lung of the pig No. 1, significant activity leakage was not observed for either left lung of the same pig or both lungs of the pig No. 2. It is confirmed by integral  $^{241}\text{Am}$  activity measurement of these lungs using ORTEC germanium spectrometer certified for volumetric sources according to [22, 23]. The technician who performed the measurements had not been informed on the value of administered activity. The values of measured activity for any of three archived lungs are similar to the values of administered activity, taking into account the measurement uncertainty of about 30% (see Table II).

### 4.2 Calculated versus Measured Spectra Comparison

To check the abilities of CEDRIP software for whole body counter calibration, the comparison of experimental versus calculation spectra was done for  $^{241}\text{Am}$ -administered pigs. CEDRIP software was used to process CT images of pigs (256×256 pixel resolution in each slice), as shown in Fig. 4, panel “a”. The pig voxel phantom was written automatically by CEDRIP as an



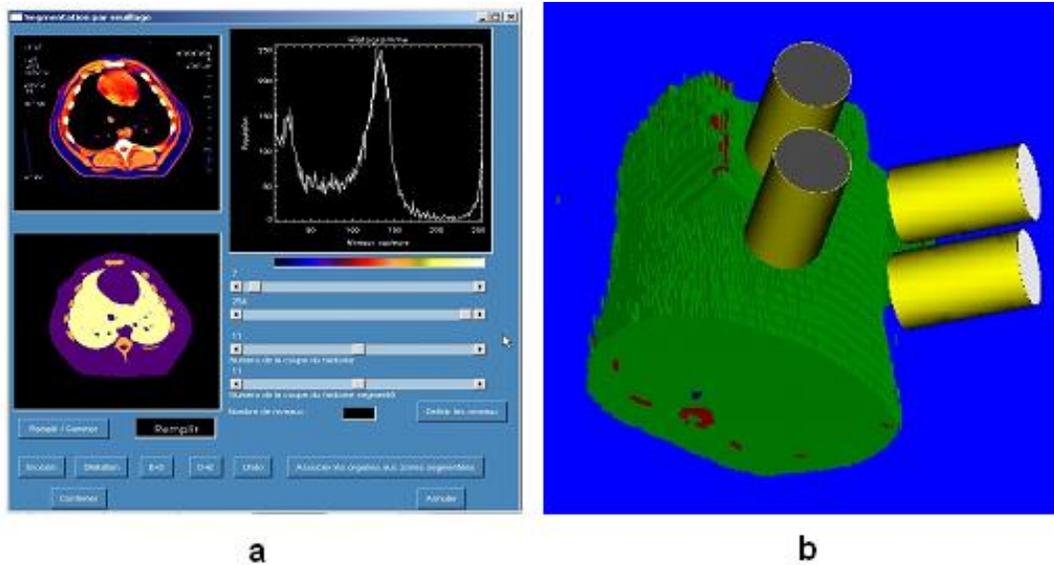
**Figure 3:** Relative right lung mass (red  $\circ$ , left scale) and administered  $^{241}\text{Am}$  activity (green  $\triangle$ , left scale) distribution, as well as absolute value of  $^{241}\text{Am}$  activity per mass unit (blue  $\square$ , right scale) as a function of distance from the top of the right lung (according to weighing and radiometry data for right lung slices).

**Table II:**  $^{241}\text{Am}$  activity of animal lungs fixed in formalin, kBq

	Pig No. 1, left lung	Pig No. 1, right lung	Pig No. 2, left lung	Pig No. 2, right lung
Administered value	13	14	27	27
Measured value	12	9.5	24	28

MCNP input data file (Fig. 4, panel “b”). MCNP4c2 calculations had the source term as the homogeneously distributed activity in the lungs for the pigs No. 1-2 (activity administered via injection) and as activity localized at multiple points for the pigs No. 3-4 (activity administered in capsules; the point positions were determined according to the capsules seen in the postmortem CT images of the animals).

Table III contains data on counting efficiency in  $^{241}\text{Am}$  principal photo peak (59.54 keV) for all animals. The examples of experimental and calculated spectra of the detectors (placed in front of the upper part of the left and right lungs of the pig No. 1) are shown in Fig. 5. MCNP4c2 calculations did not use either counting efficiency correction versus the absorbed energy or spectrum standardization, so the calculated values of Table III and Fig. 5 and are absolute ones rather than relative ones. The standard deviation in the maximum pulse counting channel for calculated spectrum is about 6% for 1 million random histories, which takes about 200 minutes of calculation time at personal computer (3 GHz, 512 Mb RAM) for spatially distributed source (pigs No. 1-2) and about 20 minutes for multiple point source (pigs No. 3-4).



**Figure 4: CT image processing to calibrate whole body counting. Panel “a”:** separation of organs and tissues by **ÆDIPE** software. Left upper window: initial CT image and segmented image below (colors correspond to tissue types); right upper window: spectrum of initial image according to the pixel brightness. **Panel “b”:** radiation transport geometry visualization by **Sabrina** software. The **MCNP** input data file was recorded automatically by **ÆDIPE** software. Color corresponds to the type of tissue or substance. Number of image voxels:  $256 \times 256 \times 23$ .

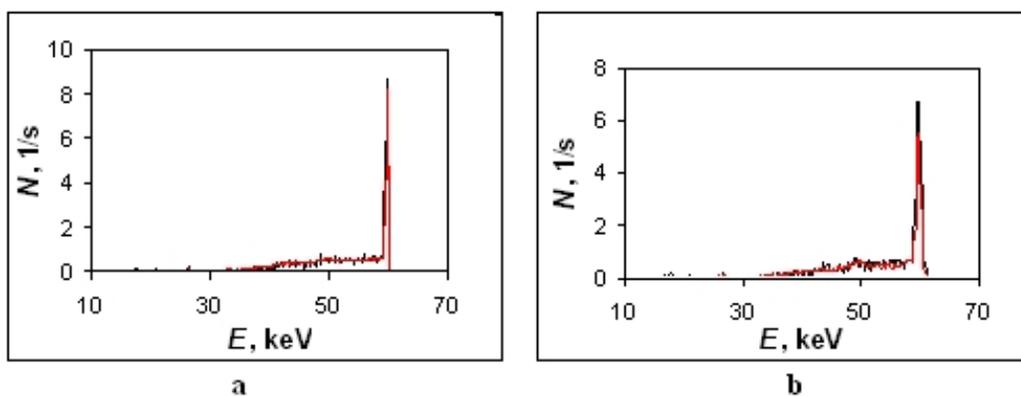
The comparison of calculation and experimental results demonstrates that calculations reproduce the pulse-height-spectrum of Canberra Industries germanium detectors with no more than 15% error for both photo peak and Compton scattering energy ranges, except for the measurement in front of the upper part of the right lung of the pig No. 1. Large discrepancy between calculation and measurement for this case is likely to be caused by the activity leakage from the right lung. This leakage is confirmed by color marks at the right lung surface and by lung slice radiometry, which points to 30% deficiency of the activity. The calculation did not take the leakage into account, so the calculated efficiency is 27% overestimated if compared with the experimental results. In general, measurements of pigs with activity administered in capsules are reproduced in calculations with higher accuracy. To understand why it is so, recall that for activity inserted in capsules we have less uncertainty for source geometry in the **MCNP** input data file. Thus, the change of activity administration method for two last pigs increased the exactitude for mathematical modeling of the measurement conditions.

## 5 CONCLUSION

A new measurement technique for whole body counting of incorporated actinides was proposed recently. The technique implies computer-assisted calibration, which uses Monte Carlo

**Table III: Experimental and calculated counting efficiency for measuring the laboratory animals in the photo peak of  $^{241}\text{Am}$  (59.54 keV).**

Pig and detector	Calculation ( $C$ ), $\text{s}^{-1}\cdot\text{kBq}^{-1}$	Experiment ( $E$ ), $\text{s}^{-1}\cdot\text{kBq}^{-1}$	Difference, $D = ((C - E)/C) \cdot 100\%$
Pig No. 1, upper left	1.23	1.05	+14
Pig No. 1, lower left	1.13	1.18	-4
Pig No. 1, upper right	1.53	1.11	+27
Pig No. 1, lower right	0.88	0.96	-9
Pig No. 2, left	0.29	0.25	+14
Pig No. 2, right	0.40	0.34	+15
Pig No. 3, left	0.25	0.23	+8
Pig No. 3, right	0.55	0.53	+4
Pig No. 4, left	0.18	0.18	0
Pig No. 4, right	0.28	0.30	-4



**Figure 5: Experimental (red line) and calculated (black line) spectra of the left (panel “a”) and right (panel “b”) detectors placed in front of the upper part of lungs of the pig No. 1 during measurement of  $\gamma$ -radiation emitted by  $^{241}\text{Am}$  injected into the lungs of the animal.**

calculations for individual patient anatomy described in terms of a voxel phantom obtained from the CT images. A special software was developed to process the CT images and to perform automatic creation of individual MCNP voxel phantoms.

The new technique was tested in a quasi-*in vivo* experiment on large-size animals (pigs) used as phantoms for measurements of  $^{241}\text{Am}$ . The measured pulse-height-spectra of high-purity germanium detectors were compared with the spectra simulated using MCNP4c2 code for individual voxel phantom geometry.

During the experiment, a new surgical method of radioactivity administration into the lungs, which is adequate to radionuclide inhalation intake, was elaborated. To provide more accurate computational representation of the measurement, the experimental protocol was improved according to the data obtained on the first animal. In particular, injection of  $^{241}\text{Am}$  nitrate solution was replaced with insertion of  $^{241}\text{Am}$ -contained capsules into the lungs of the animals. The modification of activity administration method prevented the activity leakage outside of lungs, as well as drainage along the blood vessels and bronchi, providing more certainty in radiation source positions for calculations.

In general, experimental studies show the ability of Monte Carlo calculations in voxel phantom geometry for reproducing the measurement results with high accuracy. The use of activity inserted in capsules decreased the discrepancy between measurements and calculations for the counting efficiency in the principal  $^{241}\text{Am}$  full absorption peak (59.54 keV) from 15-30% to less than 10%.

## 6 ACKNOWLEDGMENTS

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## 7 REFERENCES

1. J. Briesmeister. "MCNP — A general Monte Carlo N-particle Transport Code, version 4c," LA-13709-M (2000).
2. N. Borisov, D. Franck, L. Laval, L. de Carlan. "A New Graphical User Interface for Fast Construction of Computation Phantoms and MCNP Calculations: Application to Calibration of *in vivo* Measurement Systems," *Health Physics*, **83**, pp. 272-280 (2002).
3. D. Franck, N. Borisov, L. de Carlan, N. Pierrat, J.-L. Genicot, G. Etherington. "Application of Monte Carlo Calculations to Calibration of Anthropomorphic Phantoms Used for Activity Assessment of Actinides in Lungs," *Radiation Protection & Dosimetry*, **105**, pp. 403-408 (2003).
4. L. de Carlan, I. Aubineau-Lanièce, A. Lemosquet, N. Borisov, J.-R. Jourdain, D. Jeanbourquin, B. Le Guen, D. Franck. "Application of New Imaging and Calculation Techniques to Activity and Dose Assessment in the Case of a  $^{106}\text{Ru}$  Contaminated Wound," *Radiation Protection & Dosimetry*, **105**, pp. 219-223 (2003).

5. N. M. Borisov, O. A. Kochetkov, V. N. Yatsenko, D. Franck, L. de Carlan, S. Ts. Tsedish. "Modern Techniques in Internal Dosimetry," *Atomic Energy*, **97**, pp. 286-292 (2004; in Russian).
6. G. A. Zalikin, Yu.I. Moskalev, I. K. Petrovich. "Distribution and Biological Effects of  $^{241}\text{Am}$ ," *Radiobiology*, **8**, pp. 65-71 (1968; in Russian).
7. A. A. Puzyrev. " $^{241}\text{Am}$  Microdistribution in Some Organs of Rat after Peritoneal and Intratracheal Administration of the Isotope," *Young Scientist Conference*, Moscow, Institute of Biophysics, pp. 15-17 (1967; in Russian).
8. I. A. Tseveleva, R. A. Erokhin. " $^{241}\text{Am}$  Behavior in Rat Organism after Peritoneal and Intratracheal Administration," *Radioactive Isotopes and Organism*. Edited by Y. I. Moskalev, Medicina, Moscow, pp. 134-139 (1969; in Russian).
9. N. G. Darenskaya, I. B. Ushakov, I. V. Ivanov et al. *Extrapolation of Animal Data to Human: Principles, Approaches, Method Justification and Application in Physiology and Radiobiology (Manual)*, Istoki, Moscow — Voronezh (2004; in Russian).
10. D. G. Brown, R. E. Thomas, L. P. Jones, F. H. Cross, D. P. Sasmore. "Lethal Dose Studies with Cattle Exposed to Whole Body  $^{60}\text{Co}$   $\gamma$ -radiation," *em Radiation Research*, **15**, pp. 675-683 (1961).
11. A. A. Nelyubov. *Quantitative Features of Injuries among Dogs during Whole Body Non-uniform  $\gamma$ -ray Irradiation (Ph.D. Thesis)*, Moscow (1972; in Russian).
12. Sh. Davies, R. P. Whalen. "Americium Contamination Incident in a New York State Health Department Laboratory," *Conference of Radiation Control Program Directors at Radiological Health Section Public Health Association*, Houston, TX (1970).
13. I. Rundo, A. T. Keane, H. A. May. "Measurement of  $^{241}\text{Am}$  in the Ten-Year-Old Boy," *Assessment of Radioactive Contamination in Man*, IAEA, Vienna, pp. 579-594 (1972).
14. R. P. Whalen, Sh. Davies. "Americium Contamination Incident in a New York State Health Department Laboratory," *Radiation Data & Reports*, **13**, pp. 249-253 (1972).
15. D. E. Whalen, I. C. Rosen, N. Cohen. *In vivo* Measurement of  $^{241}\text{Am}$  in Man," *Assessment of Radioactive Contamination in Man*, IAEA, Vienna, pp. 595-678 (1972).
16. L. A. Buldakov, Z. L. Kalmykova, A. P. Nifatov et al. "Metabolism, Dosimetry and Biological Effects of Inhaled  $^{241}\text{Am}$  and  $^{239}\text{Pu}$  in Beagle Dogs," *Health Physics*, **22**, pp. 863-871 (1972).
17. *Problems of  $^{241}\text{Am}$  Radiobiology*. Edited by Yu. I. Moskalev, Atomizdat, Moscow (1977; in Russian).
18. G. N. Himmelfarb. *Anesthesia in Experimental Animals*, Tashkent, Uzbekistan (1984; in Russian).
19. A. B. Kogan, S. I. Shitov. *Physiological Experiment Technology*, Moscow (1967; in Russian).
20. D. Dehrin et al. "Indomethacin Improvement of Septic Acute Respiratory Failure in Porcine Model," *Anesthesia*, **57**, p. 134 (1982).
21. A. J. C. Holland. "Laboratory Animal Anæsthesia," *Canadian Anæsthesia Society Journal*, **20**, pp. 693-705 (1973).

22. F. K. Levochkin, I. A. Bochvar, T. N. Sokolova. "Method of  $\gamma$ -emitter Activity Assessment in Volumetric Samples of any Composition and Density and Plane Simulation Source for its Realization," *Equipment and News of Radiation Measurements*, No. 4, pp. 18-24 (2000; in Russian).
23. F. K. Levochkin, I. A. Bochvar, T. N. Sokolova, V. N. Yatsenko. "Method of Calibration of  $\gamma$ -radiation Spectrometer for Volumetric Source Activity Measurement," *Equipment and News of Radiation Measurements*, No. 4, pp. 34-39 (2003; in Russian).