Comparisons of Uniform and Discrete Source Distributions for Use in Bioassay Laboratory Performance Testing

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September 1987

**Prepared for
the U.S. Department of Energy
Assistant Secretary for
Environment, Safety, and Health
under Contract DE-AC06-76RLO 1830**

**Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
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PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE MEMORIAL INSTITUTE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

NTIS Price Codes
Microfiche A01

Printed Copy

Pages	Price Codes
001-025	A02
026-050	A03
051-075	A04
076-100	A05
101-125	A06
126-150	A07
151-175	A08
176-200	A09
201-225	A010
226-250	A011
251-275	A012
276-300	A013

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DISTRIBUTIONS FOR USE IN BIOASSAY LABORATORY
PERFORMANCE TESTING

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FOREWORD

In recent years the U.S. Department of Energy (DOE), Office of Nuclear Safety, has sponsored research to improve occupational radiation protection at its facilities. Of particular concern have been the accuracy, quality control, and performance of personnel radiation dosimeters, radiation survey instruments, and bioassay laboratories.

The work described in this report was developed as a result of testing current measurement capabilities of bioassay laboratories. The performance testing was part of a larger project that is evaluating the appropriateness of draft American National Standards Institute (ANSI) Standard N13.30, "Performance Criteria for Radiobioassay Laboratories."

This report describes computer simulation work that was designed to determine the appropriateness of using discrete radioactive sources in a bioassay phantom to approximate a uniform distribution of material. The results will be incorporated when an accreditation program for DOE bioassay laboratories is established.

E. J. Vallario, Acting Director
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EXECUTIVE SUMMARY

As part of evaluating the performance criteria of the draft American National Standards Institute (ANSI) standard on bioassay laboratory performance, draft ANSI Standard N13.30, "Performance Criteria for Radiobioassay," the Pacific Northwest Laboratory (PNL) is sending a torso phantom with radioactive material uniformly distributed in the lungs to in vivo bioassay laboratories for analysis. During development of the test protocol, the investigators became concerned over the proposed use of short half-life nuclides. If, during the testing round, the nuclide in the lungs decayed to a level close to the detection capabilities of the laboratories, results from laboratories scheduled to assay the phantom early in the round could not be meaningfully compared to results from laboratories scheduled to assay the phantom later in the round. This is because the associated relative errors would increase as the sample activity approached the laboratory's minimum detectable amount.

Although the radionuclides ultimately chosen for the studies had relatively long half-lives, future accreditation testing will require repeated tests with short half-life test nuclides. The investigators proposed to allow substitution of lung sets containing plugs of radioactive material for lung sets with uniformly distributed sources. The plugs could then be easily exchanged to maintain the desired activity level.

Computer modeling was used to simulate the major components of the phantom. Radiation transport calculations were then performed using the computer models to calculate dose rates either 15 cm from the chest or at its surface. The computer simulation compared plug-loaded phantoms to phantoms containing a uniform distribution of ^{144}Ce , ^{60}Co , and ^{40}K . The ^{144}Ce and ^{60}Co loaded in plugs were compared with uniformly distributed phantom lungs, while the plug-loaded ^{40}K was compared with uniform distributions inside the chest wall and throughout the lungs.

The simulated ^{40}K plug was located at the back of the lower heart region. The plug was assumed to contain 80 nCi of ^{40}K distributed uniformly throughout

the plug. In the calculation with the heart plug in place, no other radioactive sources were assumed to be in the phantom.

For ^{144}Ce and ^{60}Co , three configurations were used for the lung comparison tests. To provide a direct comparison, the total activity in each lung was assumed to be 320 nCi. In the first case, there were 4 source plugs in each lung with 80 nCi per plug. In the second case, there were 16 plugs in each lung, so each plug was assumed to contain 20 nCi. In the third case, each lung was assumed to contain 32 plugs with 10 nCi apiece. The locations of the source plugs were chosen to make spacing in the lung regions as even as possible.

Calculations show that, for most detector positions, a single plug containing ^{40}K located in the back of the heart provides a good approximation to a uniform distribution of ^{40}K . The approximation would lead, however, to a positive bias for the detector reading if the detector were located at the chest surface near the center. This location results in the least distance and attenuating material between the plug and the detector. Thus, the plug gives a dose rate with 95% positive bias. For other detector locations, this geometry effect is less pronounced and the bias is usually within 5% (except with the detector over the right lung, where it is 14% low).

Loading the ^{40}K in a uniform layer inside the chest wall is not a good approximation of the uniform distribution in the lungs, because most of the radionuclides would be situated close to the detector location and the only shielding would be the thickness of the chest wall. This distribution, therefore, gives dose rates to detector locations at the chest wall that are three to four times higher than the uniform distribution in the lungs.

The calculated dose rates for ^{60}Co and ^{144}Ce were similar at all calculated reference points. For both nuclides, any type of plug loading resulted in a good approximation of the uniform distribution for dose points 15 cm from the chest wall. For these locations, most relative biases were under 2%, with the highest being 4%. At the chest wall, biases up to 17% were calculated.

Plug loading is an acceptable alternative to uniform source distribution only when the measurement system incorporates a detector that is 15 cm or more

from the chest surface. When detectors are at or near the chest surface, biases up to 17% are predicted and compliance with the overall error of less than 5% specified in draft ANSI N13.30 cannot be ensured. Since the procedure used by the testing laboratory must be the same for all laboratories tested, plug source loading of phantoms used for bioassay laboratory performance testing is not recommended.

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INTRODUCTION

The work described in this document was performed by the Pacific Northwest Laboratory (PNL)^(a) in support of a project sponsored by the U.S. Department of Energy (DOE) to evaluate the performance criteria of the draft American National Standards Institute (ANSI) Standard N13.30, "Performance Criteria for Radiobioassay."^(b) The bioassay standard evaluation project is a nationwide, two-round study to test the analytical performance of in vivo bioassay laboratories and to determine the appropriateness of the performance criteria specified in the draft standard for DOE facilities.

In the intercomparison studies, a torso phantom with uniformly distributed radioactive material in the lungs was sent to in vivo bioassay laboratories for analysis. Because the phantom was to be circulated to over 20 laboratories one at a time, the concern of the investigators increased regarding the use of short half-life nuclides. If the nuclide in the lungs decayed during the testing round to a level close to the detection capabilities of the laboratories, results from laboratories scheduled to assay the phantom early in the round could not be meaningfully compared to laboratories receiving the phantom later in the round because the associated relative errors would increase as the sample activity approached the laboratory's minimum detectable amount. To solve this problem, the investigators proposed that lung sets containing plugs of radioactive material be substituted for the lung sets with uniformly distributed sources. The plugs could then be easily exchanged to maintain the desired activity level.

The purpose of the work described in this report was to estimate the magnitude of the biases that would result if plug-loaded lungs were substituted for lung sets with a uniform source distribution. The first section of this report describes the computer modeling used to test for biases introduced by nonuniform loadings. The computer code uses radiation transport calculations

(a) PNL is operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.

(b) Information on draft ANSI Standard N13.30 is available from Roscoe Hall, Savannah River Plant.

to compare simulated radiation transmission from equally spaced plugs to transmission from uniformly distributed activity. Reference Man lungs, heart, and chest wall (ICRP 1975) were modeled using regular geometric shapes. The report describes radiations from three nuclides (^{40}K , ^{144}Ce , and ^{60}Co) which were simulated in the computer calculations. Distribution of a single ^{40}K plug loading in the heart was also compared with uniform source distributions in the lungs and inside the chest wall. In a later section of the report, the bias estimates obtained were used to develop recommendations for discrete source plugs in bioassay performance testing with in vivo phantoms. As a result, conclusions and recommendations are based on these estimates of bias.

COMPUTER CALCULATIONS

Three radionuclides were simulated: ^{144}Ce , ^{60}Co , and ^{40}K . The ^{144}Ce and ^{60}Co were simulated for loading in the phantom lungs, while the ^{40}K was simulated for loading in the heart. This section describes the computer code used to calculate the radiation transport from the source to the detector, the computer modeling of the phantom, and the comparison of calculated dose rates at various detector locations.

COMPUTER CODE RNSQR

The calculation of radiation transport from the radionuclide sources in the phantom through the solid material in the phantom and into the detector was performed by the computer code RNSQR. This code is a modification of the computer code PERCS (Reece et al. 1983).

The PERCS and RNSQR codes perform radiation transport and shielding calculations using the point-kernel integration technique. The point-kernel technique divides a region containing radionuclides into a number of small volumes (or kernels), and then calculates the dose to the reference point from the radiation emitted by each kernel, which is treated as a point source. The dose calculation also accounts for the attenuating effect of any energy-absorbing materials that lie between the point-kernel and the chosen reference points. The summation of the effects of all point-kernels in a region is equivalent to integration over the entire volume of the source region. The number of point-kernels chosen to represent a region has a direct effect on the quality of the integration, but a large number of point-kernels can cause long computation times. The point-kernel integration is therefore performed iteratively by choosing an initial number of point-kernels and then increasing their number until a comparison between two successive iterations meets a given convergence criterion.

The PERCS code has a number of desirable features including its ability to handle a large number of different source regions, its flexibility in the geometrical placement of source and shield regions, and innovative algorithms that rapidly perform the three-dimensional point-kernel integration

calculations. PERCS was originally written to model contaminated pipes and tanks in a reactor and therefore has the inherent limitation that the source regions must be cylindrical. The PERCS code was modified to evaluate rectangular source regions. The modified version of PERCS was called RNDSQL, and this code was used to model the lung phantom with rectangular slabs for lungs.

PHANTOM MODEL

The arrangement of source and shield regions used by RNDSQL was designed to model the phantom regions that would be effective in containing radionuclides. The important regions in the phantom that were modeled include the chest wall, right lung, left lung, and heart.

The geometrical model used by this study is necessarily a rough approximation of the actual structure of the phantom components because the computer model uses only rectangular or cylindrical shapes for modeling doses. The dimensions of the modeled regions were chosen to approximate the same volumes as the organs that they model and to represent the average thickness of the organ for Reference Man (ICRP 1975). The positioning of the modeled regions was chosen such that the shielding effects of phantom components were closely approximated. Thus, an apparently rough approximation in the geometry can give a good estimate of detector response.

Because this study involved a comparison between uniform and point distributions of radionuclides, the approximation of using geometrical shapes for irregularly shaped organs applies equally to both distributions compared. Therefore, although the bias associated with the absolute calculated dose rates may be on the order of 25%, the bias associated with the ratios of the dose rates was expected to be less than 5%.

The heart was modeled as two rectangular solids, one on top of the other. The right lung was modeled as a single rectangular region, but the left lung was modeled as two regions, with one rotated to simulate the left lung curving behind the heart. The model regions and their dimensions are listed in Table 1, in which the model region volumes are compared to the volumes of organs in Reference Man (ICRP 1975).

TABLE 1. Dimensions of Regions in the Phantom Model

Region	Thickness, cm	Length, cm	Height, cm	Model Volume, cm ³	Reference Man Volume, cm ³
Right Lung	6	18	17	1,836	-
Left Lung				1,456	-
Upper	7	16	6	-	-
Lower	7	16	7	-	-
Lungs (total)				3,292	3,333
Heart				816	783
Upper	6	5	8	240	-
Lower	8	9	8	576	-
Chest Wall	1.52	40	20	-	-

The orientation of the regions is described by their positioning in a three-dimensional cartesian coordinate system. The coordinate system is oriented with the z-axis vertical (parallel to a line joining the phantom's waist to its head), the y-axis horizontal (parallel to a shoulder-to-shoulder line), and the x-axis anterior-posterior horizontal. The origin of the coordinate system was chosen to be on the inside of the chest wall. The region orientations are illustrated in Figure 1, looking down along the z-axis, and in Figure 2, looking along the x-axis at the front of the phantom, ignoring the chest wall.

The region orientations are precisely defined by the positioning coordinates listed in Table 2. The positioning scheme used here is used by RNDSDR to specify the locations, orientations, and size of rectangular regions. The base of a rectangular region must lie in an x-y plane, but the vertical faces can be oriented at any angle from the z-axis (these faces are not required to lie in x-z or y-z planes). In the scheme used here, a line (called the "L-R line") is drawn from the center of the left face of the region to the center of its right face (because the regions may be oriented at an angle to the axes, the choice of left and right faces may be somewhat arbitrary). The x- and y-coordinates of the ends of the L-R line are designated as x_1 , y_1 and x_2 , y_2 .

FIGURE 1. Orientation of Modeled Regions, x-y Plane

FIGURE 2. Orientation of Modeled Regions, y-z Plane

The z-coordinate of the base of the region is z_1 , and the z-coordinate of the top face is z_h . The half-thickness (t_h) is the distance from the L-R line to either side face. Figure 3 illustrates these values for the lower heart region.

The regions in the phantom were assumed to be composed of either a muscle-tissue equivalent material or a lung-tissue equivalent material. The muscle-tissue equivalent material was assumed to have a density of 1.0 g/cm^3 ,

TABLE 2. Positioning Coordinates for Lung Phantom Regions

Region	x_1 , cm	y_1 , cm	x_2 , cm	y_2 , cm	z_1 , cm	z_h , cm	t_h , cm
Chest Wall	0.76	-20	0.76	20	-10	10	0.76
Lower Heart	-4.5	-4	-4.5	4	-8	0	4.5
Upper Heart	-2.5	-3	-2.5	3	0	8	2.5
Right Lung	-9	-5	-9	-11	-9	8	9
Lower Left Lung	-7.42	3	-10.04	9.49	-8	-1	8
Upper Left Lung	-8	4	-8	11	-1	5	8

and the assumed lung-tissue equivalent material density was 0.3 g/cm^3 . The attenuation coefficients used for both materials (USOHEW 1970) were the values for tissue at the gamma energies used in this study. The muscle-tissue equivalent material was used in the chest wall and the heart regions, while the lung-tissue equivalent material was used in the three lung regions.

REFERENCE POINTS

RNDSQR was used to calculate doses to six reference points, positioned to represent the centers of the faces of detectors above the chest. The coordinates of the six reference points are listed in Table 3 and are illustrated in Figures 1 and 2.

SOURCE PLUGS

For the nonuniform loading of radionuclides in the phantom, the nuclides were assumed to be contained in plugs composed of muscle-tissue equivalent material. In one case, one plug was located in the bottom heart region; in the other cases the plugs were located in the lung regions. All plugs were assumed to be 0.8-cm-dia, 2.8-cm-long cylinders.

The heart plug was located at the back of the lower heart region, with the axis of the plug cylinder extending from the point with x-, y-, and z-coordinates of (-6.2,0,-2) to (-9,0,-2). The plug was assumed to contain

FIGURE 3. Orientation of the Modeled Lower Heart Region

TABLE 3. Reference Point Coordinates

ID	x	y	z	Comments
1	1.6	6.0	0.0	At chest wall, over left lung
2	1.6	0.0	0.0	At chest wall, center of chest
3	1.6	-6.0	0.0	At chest wall, over right lung
4	16.6	6.0	0.0	15 cm from chest, over left lung
5	16.6	0.0	0.0	15 cm from chest, center of chest
6	16.6	-6.0	0.0	15 cm from chest, over right lung

80 nCi of ^{40}K uniformly distributed throughout the plug. In the calculation with the heart plug in place, no other radioactive sources were assumed to be located in the phantom.

The lung plugs were assumed to consist of muscle-tissue equivalent material, because it is the most likely configuration for use in a phantom. This representation creates a difficulty in the calculation because the muscle-tissue equivalent plugs take the place of some of the less dense lung-tissue equivalent material. The plugs were assumed to contain either ^{144}Ce or ^{60}Co uniformly distributed.

Three different plug-loading configurations were used for the comparison tests. In the first case there were 4 source plugs in each lung, with 80 nCi per plug. In the second case there were 16 plugs in each lung. To make a comparison between these cases, the total simulated activity in each lung was kept at 320 nCi, so each plug was assumed to contain 20 nCi. In the third case, each lung was assumed to contain 32 plugs with 10 nCi apiece.

The locations of the source plugs were chosen to make the spacing in the lung regions as even as possible. Figure 4 shows the locations of the plug positions in the right lung region. Figure 4a shows the top of the lung, as viewed down the z-axis. The top layer of plug positions is shown, and the positions are labeled 1A through 4B. The A designation on the position label refers to plugs on the left side of the lung (closest to the x-axis); the B designation refers to plugs on the right side of the lung (farthest from the x-axis). Figure 4b shows a side view of the right lung, as seen looking in the +y direction. Plug locations 1 through 16 are shown for an x-z plane.

Figure 5 illustrates the locations of the source plugs in the left lung regions. Figure 5a shows the locations of plugs in the top layer of the upper left lung region; these plug locations are labeled 1A through 4B. Figure 5b shows plug locations 9A through 12B, from the top layer of the lower left lung region. Figure 5c is a side view of the two left lung regions, with the lower lung rotated so that all of the plug axes would be parallel. This orientation gives a clearer view of the locations of the plugs with respect to the left lung region boundaries. The locations of plugs 1 through 16 are illustrated.

a. Top View

b. Side View

FIGURE 4. Source Spacing, Modeled Right Lung Region

FIGURE 5. Source Spacing, Modeled Left lung Region

FIGURE 5. (contd)

Table 4 shows which source plugs were used for each of the three configurations (4, 16, or 32 source plugs).

TABLE 4. Source Plug Locations Used in Calculations

<u>Left Lung</u>				<u>Right Lung</u>			
<u>Location</u>	<u>Number of Plugs</u>			<u>Location</u>	<u>Number of Plugs</u>		
	<u>4</u>	<u>16</u>	<u>32</u>		<u>4</u>	<u>16</u>	<u>32</u>
1A	X	X	X	1A	X	X	X
1B			X	1B			X
2A			X	2A			X
2B		X	X	2B		X	X
3A		X	X	3A		X	X
3B			X	3B			X
4A			X	4A			X
4B		X	X	4B		X	X
5A		X	X	5A			X
5B			X	5B		X	X
6A			X	6A		X	X
6B		X	X	6B			X
7A		X	X	7A			X
7B	X		X	7B	X	X	X
8A			X	8A		X	X
8B		X	X	8B			X
9A		X	X	9A		X	X
9B			X	9B			X
10A	X		X	10A	X		X
10B		X	X	10B		X	X
11A		X	X	11A		X	X
11B			X	11B			X
12A			X	12A			X
12B		X	X	12B		X	X
13A		X	X	13A			X
13B			X	13B		X	X
14A			X	14A		X	X
14B		X	X	14B			X
15A		X	X	15A			X
15B			X	15B		X	X
16A			X	16A		X	X
16B	X	X	X	16B	X		X

RESULTS

Dose rates at six reference points were calculated for the following three simulated nuclide loadings: ^{40}K , ^{144}Ce , and ^{60}Co . The comparisons are shown as relative biases, defined as the differences between the compared dose rates divided by the uniform in-lung dose rates (the relative bias would be zero for perfect agreement).

POTASSIUM-40

Three different radionuclide loadings were used to calculate dose rates resulting from ^{40}K distributed in the phantom:

- 80 nCi in a plug in the heart
- 80 nCi distributed uniformly inside the chest wall
- 80 nCi distributed uniformly in the lungs.

The calculated dose rates at each of the six detectors for the three different nuclide loadings are shown in Table 5.

Table 6 shows a comparison of the dose rates calculated using the configuration of a source plug in the heart to the dose rates calculated using a uniform distribution of ^{40}K in the lungs. A comparison of the dose rates using the distribution of ^{40}K inside the chest wall to the dose rates using a uniform distribution in the lungs is also shown in Table 6.

TABLE 5. Calculated Dose Rates from ^{40}K

Reference Points	Calculated Dose Rates, mrad/h		
	Plug in Heart	Inside Chest Wall	Uniform in Lungs
At chest wall, over left lung	4.79×10^{-4}	1.72×10^{-3}	5.04×10^{-4}
At chest wall, center	6.82×10^{-4}	1.78×10^{-3}	4.37×10^{-4}
At chest wall, over right lung	4.79×10^{-4}	1.67×10^{-3}	5.55×10^{-4}
15 cm from chest, over left lung	9.47×10^{-5}	1.79×10^{-4}	9.10×10^{-5}
15 cm from chest, center	1.01×10^{-5}	1.90×10^{-4}	9.76×10^{-5}
15 cm from chest, over right lung	9.47×10^{-5}	1.79×10^{-4}	9.56×10^{-5}

TABLE 6. Comparison of Dose Rates from ^{40}K

Reference Point	Relative Bias	
	Plug in Heart	Inside Chest Wall
At chest wall, over left lung	-0.05	+2.41
At chest wall, center	-0.56	+3.07
At chest wall, over right lung	-0.14	+2.01
15 cm from chest, over left lung	+0.04	+0.97
15 cm from chest, center	+0.04	+0.95
15 cm from chest, over right lung	-0.01	+0.87

CERIUM-144

Four different radionuclide distributions in the phantom were used to calculate dose rates at the six detector locations:

- 320 nCi uniformly distributed in each lung
- 32 plugs (10 nCi per plug) in each lung
- 16 plugs (20 nCi per plug) in each lung
- 4 plugs (80 nCi per plug) in each lung.

Table 7 lists the results of these calculations.

The comparison of calculated dose rates from different plug loadings to the uniform distribution of ^{144}Ce in the lungs is shown in Table 8. The values listed in Table 8 are the ratios of the relative biases of the dose rates to the dose rates at the same location due to a uniform distribution in the lungs.

TABLE 7. Calculated Dose Rates from ^{144}Ce

Reference Points	Calculated Dose Rates, mrad/h			
	Uniform in Lungs	32 Source Plugs	16 Source Plugs	4 Source Plugs
At chest wall, over left lung	0.00159	0.00156	0.00174	0.00176
At chest wall, center	0.00127	0.00113	0.00119	0.00133

TABLE 7.. (contd)

Reference Points	Calculated Dose Rates, mrad/h			
	Uniform in Lungs	32 Source Plugs	16 Source Plugs	4 Source Plugs
At chest wall, over right lung	0.00151	0.00138	0.00138	0.00126
15 cm from chest, over left lung	0.000272	0.000272	0.000274	0.000282
15 cm from chest, center	0.000288	0.000284	0.000286	0.000293
15 cm from chest, over right lung	0.000275	0.000270	0.000272	0.000275

TABLE 8. Relative Bias in Calculated Dose Rates from ^{144}Ce

Reference Points	Relative Bias in Calculated Dose Rates		
	32 Source Plugs	16 Source Plugs	4 Source Plugs
At chest wall, over left lung	-0.02	+0.09	+0.11
At chest wall, center	-0.11	-0.06	+0.05
At chest wall, over right lung	-0.09	-0.09	-0.17
15 cm from chest, over left lung	0.00	+0.01	+0.04
15 cm from chest, center	-0.01	-0.01	+0.02
15 cm from chest, over right lung	-0.02	-0.01	0.00

COBALT-60

For ^{60}Co , four loadings were used to calculate the dose rates at the following six detector locations:

- 320 nCi uniformly distributed in each lung
- 32 plugs (10 nCi per plug) in each lung

- 16 plugs (20 nCi per plug) in each lung
- 4 plugs (80 nCi per plug) in each lung.

The results of these calculations are listed in Table 9. The relative bias in the calculated dose rates compared to the dose rates from a uniform distribution of ^{60}Co in the lungs is shown in Table 10.

TABLE 9. Calculated Dose Rates from ^{60}Co

Reference Points	Calculated Dose Rates, mrad/h			
	Uniform in Lungs	32 Source Plugs	16 Source Plugs	4 Source Plugs
At chest wall, over left lung	0.0735	0.0725	0.0715	0.0814
At chest wall, center	0.0598	0.0536	0.0535	0.0628
At chest wall, over right lung	0.0698	0.0644	0.0638	0.0590
15 cm from chest, over left lung	0.0125	0.0125	0.0125	0.0129
15 cm from chest, center	0.0132	0.0130	0.0130	0.0134
15 cm from chest, over right lung	0.0127	0.0125	0.0125	0.0127

TABLE 10. Relative Bias in Calculated Dose Rates from ^{60}Co

Reference Points	Relative Bias in Calculated Dose Rates		
	32 Source Plugs	16 Source Plugs	4 Source Plugs
At chest wall, over left lung	-0.01	-0.03	+0.11
At chest wall, center	-0.10	-0.11	+0.05
At chest wall, over right lung	-0.03	-0.09	-0.15
15 cm from chest, over left lung	0.00	0.00	+0.03
15 cm from chest, center	-0.02	-0.02	+0.02
15 cm from chest, over right lung	-0.02	-0.02	0.00

CONCLUSIONS AND RECOMMENDATIONS

The simulations described in this report indicate that a single plug containing ^{40}K located in the back of the heart is a good approximation to a uniform distribution of ^{40}K throughout the lungs for five of the six reference points tested. However, a single plug in the heart would lead to a high bias when the dose rate at the center of the chest surface is compared to a uniform distribution of ^{40}K . A detector placed in this position would be closer to the source with less attenuating material intervening than for the other reference points. Thus, the plug gives a dose rate at this point with a 56% positive bias. For other reference points, the masses of attenuating material for the point and uniform distributions are similar and the biases are less than 5% (except at the chest surface over the right lung with a 14% negative bias).

Loading the ^{40}K in a uniform layer inside the chest wall would not be a good approximation to a uniform distribution in the lungs because most of the radionuclide would be close to the reference point, and the only absorbing material would be the chest wall. This distribution, therefore, gives dose rates to a detector at the chest wall that would be three to four times higher than those measured with a uniform source distribution in the lungs.

The comparison calculations for ^{60}Co were very similar to the calculations for ^{144}Ce . Each of the three plug loadings resulted in a very good approximation to the uniform distribution for reference points 15 cm away from the chest wall. For these reference points, relative biases were less than 4%.

For reference points at the chest wall, the configuration of four source plugs per lung produced less desirable biases than the other two loadings. The estimated dose rate to a detector placed over the left lung would have an 11% positive bias for both nuclides. Over the right lung, negative biases of 17% and 15% for ^{144}Ce and ^{60}Co , respectively, were estimated. At the center of the chest wall, a positive 5% bias was estimated for both nuclides. These values are still in reasonable agreement with those of other loadings, but a choice of four different plug locations may have given a poorer comparison.

Calculations showed that there was not much difference in expected bias of calculated dose rates at the chest wall between loadings of 16 plugs per lung and 32 plugs per lung. The cases with 32 plugs per lung gave slightly lower biases than cases with 16, but all estimated biases were small relative to other biases of significance in the bioassay process. In all cases the deviation from the uniform distribution dose rate was less than 12%, with most relative biases less than 10%.

If a bias of 5% or less is considered acceptable, no plug loading configuration of ^{144}Ce or ^{60}Co provided a good approximation to a uniform source distribution in the lungs for use with counting systems where the detector is positioned near the chest surface. Nor would a single source plug in the heart adequately simulate the uniform distribution of ^{40}K in the lungs. Plug loading would be an acceptable alternative to uniform source distributions only when the measurement system incorporates a detector that is 15 cm or more from the chest surface. Because of this limitation, plug source loading of phantoms used for bioassay laboratory performance testing is not recommended.

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