Instructions for Using Gamma Cameras to Assess Internal Contamination from Inhaled Radioisotopes

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PREFACE

During the past three years, S. Cohen and Associates, sponsored by the Centers for Disease Control and Prevention, has prepared a series of reports under the title "Use of Radiation Detection, Measuring, and Imaging Instruments to Assess Internal Contamination from Inhaled Radionuclides."

Part I of the series describes a study to evaluate radiation detection and imaging systems commonly found in hospitals to determine their suitability for rapidly scanning individuals for internal contamination, and to develop recommendations regarding their potential use (Anigstein et al. 2007a). That report describes the measurement of count rates from single discrete radioactive sources of ^{60}Co, ^{137}Cs, ^{192}Ir, and ^{241}Am, using a Philips AXIS gamma camera, an Atomlab thyroid uptake system, and a Ludlum waste monitor.

Part II extends the earlier investigation by using realistic anthropomorphic phantoms to study the responses of four instruments to five radionuclides distributed in the lungs (Anigstein et al. 2007b). The experimental measurements were performed on sources in the lung region of a Rando Phantom—an anthropomorphic phantom that contains a human skeleton embedded in a tissue-equivalent urethane rubber. Count rates from each of five radionuclides—^{60}Co, ^{90}Sr, ^{137}Cs, ^{192}Ir, and ^{241}Am—were measured on a Siemens e.cam gamma camera, an Atomlab thyroid probe, a Ludlum survey meter, and a Ludlum waste monitor. In a preliminary analysis, the Los Alamos MCNPX (Monte Carlo N Particle eXtended) computer code was used to calculate calibration factors that relate count rates on these instruments to lung burdens of each of the five nuclides. A mathematical model of each of the instruments was constructed, using engineering drawings and other data obtained from the manufacturers. This model was combined with an MCNP model of a Rando Phantom, constructed from CT scans of this phantom (Wang et al. 2004). The combined model was used to simulate the response of each instrument to sources in the phantom. The agreement between the calculated and measured responses validates the MCNP models of the four instruments.

Part III (Anigstein et al. 2007c) extends the investigations to the Philips SKYLight camera. The study was narrowed to three of the five radionuclides reported in Part II: ^{60}Co, ^{137}Cs, and ^{241}Am. This study encompassed measurements and corresponding MCNP simulations of sources of the three nuclides located in the lung region of a Rando Phantom. In addition, measurements and simulations were carried out of the source capsules in air. The agreement between the calculated and measured responses validates the MCNP model of this instrument.

Part IV (Anigstein and Olsher 2007) develops calibration factors that enable the use of gamma cameras for assessing inhaled intakes of radionuclides. The study utilized biokinetic models to determine the retention of inhaled activity in the body and the distribution of such activity among various anatomical regions as a function of time following exposure (ORNL 2006). Normalized count rates from activities of four gamma-emitting radionuclides—^{60}Co, ^{137}Cs, ^{192}Ir, and ^{241}Am—in various anatomical regions of adult men and women and children of various ages were calculated by MCNPX. Adult men and women were represented by the NORMAN and

NAOMI voxel phantoms (Dimbylow 1998, 2005), while children were represented by the revised ORNL phantom series described by Han et al. (2006). The Siemens e.cam and Philips SKYLight gamma cameras were represented by models developed during the studies described in Parts II and III, respectively.

The present work distills the results of the previous studies into a form that is usable by hospital personnel. The first part of these instructions provides detailed directions to the nuclear medicine technologist on using the camera equipment to determine the activities of the four radionuclides for which calibration factors were developed. The second part describes calculations to assess the initial intakes of radionuclides, based on the count rates measured by the technologist. These calculations can be performed by the technologist, a health physicist, or a physician.

The authors gratefully acknowledge the support and assistance of a number of individuals and organizations, without whom this work would not have been possible. Keith Eckerman of the Oak Ridge National Laboratory provided advice and information on the use of the DCAL software system. Peter Dimbylow of the Radiation Protection Division of the Health Protection Agency in the United Kingdom provided access to the NORMAN and NAOMI databases and furnished additional data and information on the use of these models. Wesley Bolch, Professor of Radiological and Biomedical Engineering at the University of Florida, provided the MCNP models of the revised ORNL phantom series. Julie Timins, Attending Radiologist, Christ Hospital, Jersey City, NJ, reviewed these instructions and made thoughtful comments and recommendations.

INSTRUCTIONS FOR USING GAMMA CAMERAS TO ASSESS INTERNAL CONTAMINATION FROM INHALED RADIOISOTOPES

A radiological emergency, such as the detonation of a radioactive dispersion device (RDD or "dirty bomb"), could lead to the inhalation of airborne radioactive material by a large number of people. There would be a need to rapidly assess this inhaled activity and determine the need for medical intervention. One instrument that could be used for this purpose is a gamma camera, commonly used in performing imaging studies in nuclear medicine.

1 INTRODUCTION

Due to their large areas, the thallium-doped sodium iodide (NaI[Tl]) crystals in gamma cameras are highly sensitive detectors of penetrating photon radiation from gamma-emitting radioisotopes, similar to the radiopharmaceuticals used in nuclear medicine. With the lead collimators removed, these instruments can detect and measure relatively low levels of radiation from radioisotopes inside the body.

The purpose of this set of instructions is to enable the nuclear medicine technologist to use a gamma camera to assess the activity of a known radioisotope inhaled by an exposed individual at a known time after intake. These procedures apply if:

- There is a single radioisotope that has been identified
- The duration of exposure was brief compared to the elapsed time since the exposure
- The time when the exposure occurred is known

Procedures have been developed for the assessment of four radioisotopes: ^{60}Co, ^{137}Cs, ^{192}Ir, and ^{241}Am. Procedures for other isotopes are not available at this time. Procedures have been developed for two gamma camera models: the Siemens e.cam and the Philips SKYLight (cameras similar to the SKYLight were produced by ADAC Laboratories, now a division of Philips, and are often referred to as ADAC cameras). Section 6 explains how these procedures can be adapted to other makes and models of gamma cameras. Because of differences in control consoles and software between different installations, even for the same model of gamma camera, these procedures are generic in nature. Each facility may wish to develop more detailed instructions that are consistent with the exact configuration of its gamma cameras and with its normal operating procedures.

The remainder of these instructions consists of directions to the nuclear medicine technologist. The calculations described in Section 4.2 should be performed by a health physicist; however, they can also be done by a physician, a technologist, or another qualified health care professional.

2 PRELIMINARY STEPS

2.1 Preparation of Nuclear Medicine Facility

Prior to receiving any exposed individuals, clear the nuclear medicine area of all radiation sources so as to reduce the radiation background, which could interfere with the assessments of the exposed individuals. All patients who have been administered radiopharmaceuticals and still retain any activity in the body should be cleared from the nuclear medicine area. Also remove any radioactive materials, such as radiopharmaceuticals or calibration or flood sources.

Obtain a survey meter—a Ludlum MicroR meter, an ionization chamber, or a G-M counter—and survey the area for any stray sources of radiation. Check the background reading on the meter and make a note of it—you will need this information later.

2.2 Setting up Gamma Camera

As the first step in setting up the camera, remove the collimators, and cover the detectors to protect them from contamination. You can use plastic sheeting, plastic bags, plastic blue chucks, or any thin, lightweight materials. Next, set up energy windows specific to the camera and to the radioisotope. Set the same energy windows on both camera heads.

2.2.1 Energy Windows

Siemens e.cam
Use six energy windows with the Siemens camera for the most accurate results in counting ^{60}Co, ^{137}Cs, or ^{192}Ir. Group all six windows together in a single frame. Use two energy windows for counting ^{241}Am. These windows are listed in Table 1.

Table 1. Primary Set of Energy Windows for Siemens e.cam Gamma Camera

Isotope:	Co-60, Cs-137		Ir-192		Am-241	
Window No.	Peak (keV)	Width (%)	Peak (keV)	Width (%)	Peak (keV)	Width (%)
1	41	50	35	50	35	50
2	69	50	59	50	59	50
3	116	50	99	50		
4	194	50	166	50		
5	324	50	277	50		
6	541	50	462	50		

If setting six windows is too cumbersome, or if the camera does not accept these windows, use an alternate set of three windows for counting ^{60}Co, ^{137}Cs, or ^{192}Ir. Group these windows in a single frame. These alternate windows are listed in Table 2.

Table 2
Alternate Set of Energy Windows for ^{60}Co, ^{137}Cs, and ^{192}Ir on Siemens e.cam Gamma Camera

Isotope:	Co-60		Cs-137		Ir-192	
Window No.	Peak (keV)	Width (%)	Peak (keV)	Width (%)	Peak (keV)	Width (%)
1	101.3	50	97.3	50	96.0	50
2	168.9	50	162.3	50	160.1	50
3	281.6	50	270.6	50	266.9	50

Philips SKYLight
Use a set of two energy windows on the Philips camera to count ^{60}Co, ^{137}Cs, or ^{192}Ir. Set a single energy window to count ^{241}Am. These windows are listed in Table 3.

Table 3. Energy Windows of Philips SKYLight Gamma Camera

Isotope:	Co-60		Cs-137		Ir-192		Am-241	
Window	Peak (keV)	Width (%)	Peak (keV)	Width (%)	Peak (keV)	Width (%)	Peak (keV)	Width (%)
1	124.6	86	191.2	86	94.7	86	51.3	83
2	312.6	86	479.6	86	237.5	86		

2.2.2 Counting Background

After setting the energy window appropriate to the radioisotope that is the likely contaminant, perform a static 2-minute acquisition and record the background count in each detector. Count for 10 minutes if the likely contaminant is ^{241}Am. You can enter “background” as the patient name. If the background counts are unusually high, or if the background of one detector is very different from the other, check for any stray sources of radiation in the area.

Repeat the background counts after each patient if the patient count rate is more than twice the previous background. Subtract the new background counts from the patient counts in recording the net counts for that patient. Check for radiation sources, including exposed patients in the vicinity of the camera room, if the background in either detector has increased significantly.

2.3 Preparing Patient

Prior to the patient being referred to the nuclear medicine department, he/she should undergo a thorough external decontamination by the emergency responders or by the hospital’s health physics personnel. This may require a complete change of clothing, showering or other forms of decontamination of the entire body, including the hair. Do not allow any exposed individuals into the nuclear medicine area unless they are free of external radioactive contamination.

3 PERFORMING ASSESSMENT

Admit only one patient at a time to the area near the gamma camera. Have other patients wait well away from the camera room.

3.1 Preliminary Screening

Before using the gamma camera to measure internal activity, check if the activity level of the patient could exceed the maximum count rate of the camera, which is typically 350 kcps or higher for the cameras currently sold in the United States. To do this, hold a survey meter one meter away from the patient at the waist level. Record the reading and subtract the background that you previously recorded for this instrument. Note the exposure rate in the patient record.

If the exposure rate exceeds the value in Table 4 for the given isotope, note that fact in the patient record and inform the appropriate medical or health physics personnel that the activity in the patient may be higher than the value calculated from the count rate in the gamma camera.

Table 4. Maximum Exposure Rates at 1 m (μR/h)

Isotope	Exposure rate
Co-60	40
Cs-137	55
Ir-192	45
Am-241	30

3.2 Positioning Patient

The calibration factors for each isotope for the Siemens and Philips gamma cameras were calculated from computer simulations in which life-like representations of pediatric patients of different ages and adults of both sexes were placed in positions similar to those used clinically for lung or whole-body scans. It is therefore important to place the patient in the same position; otherwise, the count rates cannot be used to estimate the intake of radioisotopes.

Since the collimators are removed, it may be necessary to set the collision override to enable movement of the camera heads and to use the camera system to perform acquisitions. In all cases, keep a distance 5

Figure 1. Pediatric Patient with Philips SKYLight (Garrard 2007)

cm (about 2 inches) between the camera and the nearest portion of the body. Such a separation is needed because, without a collimator, there is no pressure-sensitive alarm to protect the patient from potential injury by contact with the detector, nor is the detector protected from being damaged by contact with the patient.

If a child is old enough to stand up and follow directions, have her stand between the two camera heads, as shown in Figure 1. Place younger children on the scanner bed and restrain them as necessary.

Unlike the acquisition of an image using collimators, when any movement of the patient would result in a blurred image, slight movements (of a fraction of an inch) will not affect the accuracy of the counts.

Figures 2–15 show cross-sectional views in the median plane of children of various ages and of adults of both sexes, and their positions with respect to the gamma cameras. These figures were created by the computer models used to generate the calibration factors for the two gamma cameras. The models of children shown in Figures 2–11 are stylized geometrical forms which were used to model the distribution of the radioisotopes in the body as a function of time after intake. The models of adults shown in Figures 12–15 are based on MRI scans of normal volunteers, adjusted to the heights and weights of reference adults listed in Table 5.

Table 5. Height and Weight of Reference Persons

Age (sex)	Height		Weight	
	cm	in	kg	lb
Newborn	51	20	3.5	7.7
1 y	76	30	10	22
5 y	109	43	19	42
10 y	138	54	32	71
15 y	167	66	56	123
Adult male	176	69	73	161
Adult female	163	64	60	132

Source: ICRP 2002, Table 2.9

Use these diagrams to position the patients. If using the Siemens e.cam camera, keep the two camera heads facing each other (at the same height, if each head is in the vertical position). For the Philips camera, set the two detectors at different heights for all but the smallest pediatric patients to afford a better view of the internal organs.

The heights of the children represented by stylized diagrams shown in Figures 2–11 are based on average sizes of children of the indicated age, which are listed in Table 5. The actual size will of course vary from one individual to another. Find the age of the reference person in Table 5 that is nearest *in height* to the actual patient and use the diagram and the description of the position corresponding to that age to position the patient.

Position an infant so that the entire body is centered on the field of view (FOV) of each camera. Position a one-year-old with the top of the head at the top of the FOV, which encompasses all but the lower legs. (With the collimator removed, counts are registered from regions of the body outside the normal field of view, but with reduced efficiencies.) Position a 5-year-old with the lower pelvis at the bottom edge of the FOV. When counting a 10-year-old with a Siemens camera, center the detectors on the region extending from the nose to the base of the trunk. (A significant fraction of the inhaled activity is contained in the anterior nasal cavity during the first day following exposure.) Position the two heads of the Philips SKYLight such that the nasal cavity of the 10-year-old is included in the FOV of the anterior detector, while all the major organs in the trunk are within the FOV of the posterior detector. The positions of the 15-year-old and the adults are typical of adults undergoing lung scans.

The nose of the adult male in Figures 12 and 13 is touching the camera. This is due to the rigidity of the figure in the computer model: the real patient would tilt his head back. In the sagittal sections of the adult female shown in Figures 14 and 15, the buttocks appear flattened due to the supine position of the subject during the MRI scan. The spacing of the camera heads shown in these figures maintains a 5-cm distance from the natural contours of the body of a patient standing erect. Because the median plane lies between the lower legs of both individuals, only the upper portions of the legs are shown in Figures 12–15.

For longer acquisition times, or if the patient is not comfortable standing, a stool may be used by adults or taller children, provided the position of the trunk is approximately that shown in the appropriate diagram. Alternatively, the patient, especially a young child, can lie on the imaging table. Since the calibration factors are based on a 5-cm space between the patient and the aluminum window, it may be necessary to position the lower detector as close as possible to the bottom of the table. Estimate and record the distance between the front of the aluminum window and the lowermost part of the body. If a patient is not comfortable being placed in the narrow space between two camera heads, the acquisition can be performed with a single head in the anterior position, as described above.

3.3 Acquiring Counts

Enter the name of the patient to begin an acquisition. If the patient has not been assigned a patient number, assign numbers sequentially to successive patients. Weigh or estimate the weight of children—this information is needed for calculating the intake.

Counts should be acquired for one minute. Count for 10 minutes if the likely isotope is ^{241}Am. Record the counts from each detector, as well as the acquisition time.

4 CALCULATING INHALED ACTIVITY

4.1 Calculating Count Rate

Calculate the count rate in kcpm (thousands of counts per minute) separately for each detector by dividing the total counts by the acquisition time in minutes. Some systems display the total as kcounts. If the total is displayed as actual counts, divide by 1,000. Next, calculate the background count rate for each detector, and subtract the background from the calculated count rate *for that detector*. The two detectors will usually have different count rates.

4.2 Calculating Intake

Tables 6–12 list calibration factors for assessing activities inhaled by exposed individuals at several different times after intake. These factors relate the count rate measured by a given camera to the intake of a given radioisotope with a given Lung Absorption Type.

To assess the initial activity inhaled by an exposed individual, you may need to know the Lung Absorption Type of the isotope, which depends on its chemical form. Because all forms of ^{137}Cs belong to the same Lung Absorption Type, as do all forms of ^{241}Am, there is a single set of calibration factors for each of these isotopes. There are two sets of calibration factors for ^{60}Co and three sets for ^{192}Ir. Unspecified compounds of cobalt are Type M, while oxides, hydroxides, halides, and nitrates are Type S. Unspecified compounds of iridium are Type F; metallic iridium, halides, and nitrates are Type M; while oxides and hydroxides are Type S (ICRP 1994, Annexe F).

When assessing a child, use the calibration factors for a child nearest in *weight* to that of the exposed individual. The weights of reference individuals are listed in Table 5. Use the calibration factors appropriate to the sex of an adult. Next, find the time post intake closest to the time elapsed between the peak exposure and the time the counts were taken. Then find the calibration factor in the column corresponding to the gamma camera and set of energy windows used in measuring the count rate. Linear interpolation may be used to determine a calibration factor for a time between two consecutive time steps, especially if there is a large difference between the calibration factors for the two time steps.

Multiply the count rate, in thousands of counts per minute (kcpm), by the appropriate calibration factor to determine the inhaled activity in becquerels (Bq). Divide by 37,000 to obtain a value in microcuries (µCi). Perform separate calculations for the count rates from the detectors in the anterior and posterior positions. Take the average of the two results. However, if the patient was counted on the imaging table, and if the count rate from the posterior detector (the one beneath the table) yields a lower intake than the one from the anterior detector, use the higher value of the estimated intake.

5 EXAMPLES

5.1 Example of Gamma Camera Procedure

The procedures to be followed by the nuclear medicine technologist are illustrated by the following example.

You are operating a Philips SKYLight gamma camera. You were alerted to expect patients that have been exposed to airborne dust contaminated with ^{241}Am. You send all ambulatory patients who have been administered radioisotopes out of the nuclear medicine area and arrange for the transportation of non-ambulatory cases. You remove all radiopharmaceuticals, check sources, flood sources, and other radioactive materials to a shielded area away from the gamma camera. You obtain a survey meter and read and record a background exposure rate of 5 μR/h. You walk around the room with the meter and see that the reading is steady, indicating that there are no stray sources left in the area.

You remove both collimators from the camera and cover the camera heads with plastic sheeting. You then set an energy window with a peak of 51.3 keV and a width of 83%. You perform a static acquisition for a preset time of 10 minutes. When the acquisition stops, you note that 98.9 kcounts were acquired in Detector 1 and 72.2 kcounts in Detector 2. You record this information in an appropriate log book.

You now receive the patient: a 12-year-old male who is 160 cm (63 in) tall and weighs 50 kg (110 lb). You enter this information in the patient record. You hold the survey meter 1 meter (~3 ft) away from the patient at waist level. The meter reads 5–6 μR/h, which is less than 1 μR/h above background. You note this in the patient record. Since the reading is less than 30 μR/h above background, the maximum exposure rate from ^{241}Am listed in Table 4, the count rate on the gamma camera will not exceed the maximum rate for this instrument.

You check Table 5 and see that the patient's height is closest to the height of the reference 15-year-old. You position him between the two heads of the camera, facing Det. 1. You position the camera heads as shown in Figure 11, which illustrates the 15-year-old with the Philips SKYLight. You perform a 10-minute static acquisition and note that 122 kcounts were acquired in Det. 1 and 351 kcounts in Det. 2. You record these counts in the patient record, together with the most recent background counts which were listed in the log book.

Since both the background counts and the patient counts were acquired for 10 minutes, you subtract the total background counts from the patient counts in each detector to get the net counts. Since the anterior patient counts in this example are shown to the nearest kcounts, you round off the background counts.

Anterior counts: 122 − 99 = 23 kcounts

Posterior counts: 80.3 − 72.2 = 8.1 kcounts

Since the counting time was 10 minutes, you divide each value by 10:

Anterior count rate: 2.3 kcpm

Posterior count rate: 0.81 kcpm

You enter this information in the patient record, along with the time and date of the acquisition.

5.2 Example Calculation of Intake

The calculation of the estimated intake, which should be performed by a health physicist, a physician, a technologist, or another qualified health care professional, is illustrated by the following example. The patient is the same one described in Section 5.1.

To estimate the inhaled activity, first obtain the anterior and posterior count rates, recorded in units of kcpm (thousands of counts per minute). In the present example, the release of radioactive dust occurred at 2 p.m., while the counts were recorded at approximately 5 p.m., 3 hours later. The patient weighs 50 kg. According to Table 5, this is nearest to the weight of a 15-year-old. Therefore, you use the calibration factors for a 15-year-old, even though the patient is 12 years old. Since the isotope is presumed to be ^{241}Am, you look in Table 12 under "15-y-old" and calculate calibration factors for 3 hours post exposure by interpolating between the 2-h and 4-h factors for the Philips SKYLight, the camera used to measure the count rates. You obtain the following values:

Anterior factor: $$\frac{780 + 861}{2} = 821 \text{ Bq/kcmp}$$

Posterior factor: $$\frac{2{,}245 + 2{,}336}{2} = 2{,}291 \text{ Bq/kcmp}$$

You calculate the intake separately for the anterior and posterior counts:

Intake (anterior): $2.3 \times 821 = 1{,}888$ Bq

Intake (posterior): $0.81 \times 2{,}291 = 1{,}856$ Bq

Taking the average of the two values, you report the estimated intake as 1,872 Bq (50.6 nCi).

Note that this is the total inhaled activity, and includes a fraction that was promptly expelled. The total inhaled activity is the relevant quantity for estimating prospective doses.

6 USING OTHER MODELS OF GAMMA CAMERAS

These instructions may be applicable to some other models of gamma cameras, provided they meet the following criteria:

- The detectors are equipped with ⅜-inch (0.95 cm) NaI(Tl) crystals. This is the most common thickness; however, some models have crystals up to 1-inch thick. The calibration factors for thicker crystals would be significantly different than the ones tabulated with these instructions.

- The field of view (FOV) is rectangular and approximately 51 × 38 cm (20 × 15 inches) or larger. Cameras that are 1 inch smaller in either dimension are acceptable. (The FOV of the Philips SKYLight is in the shape an irregular octagon—a rectangle with the corners cut off. Such a shape is acceptable for this purpose.)

- The camera can accept one of the sets of energy windows listed in Table 1 or 3. If using windows from Table 1, use the patient positions for the Siemens camera; likewise, use the positions for the Philips camera with the windows in Table 3.

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POSITION OF PATIENT WITH RESPECT TO GAMMA CAMERA

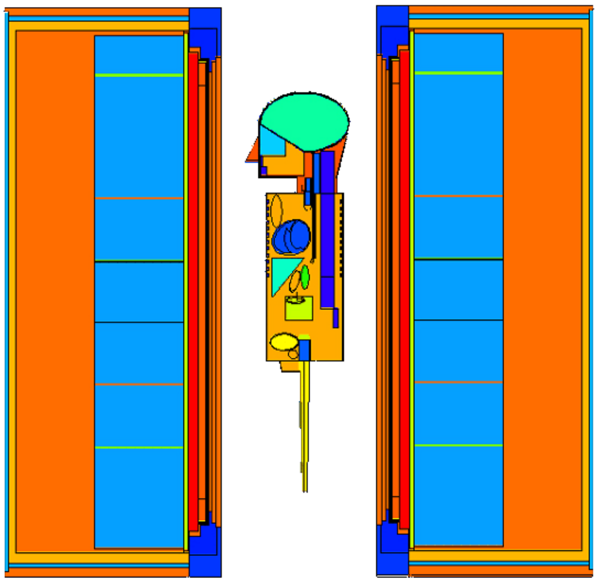

Figure 2. Infant–Siemens e.cam

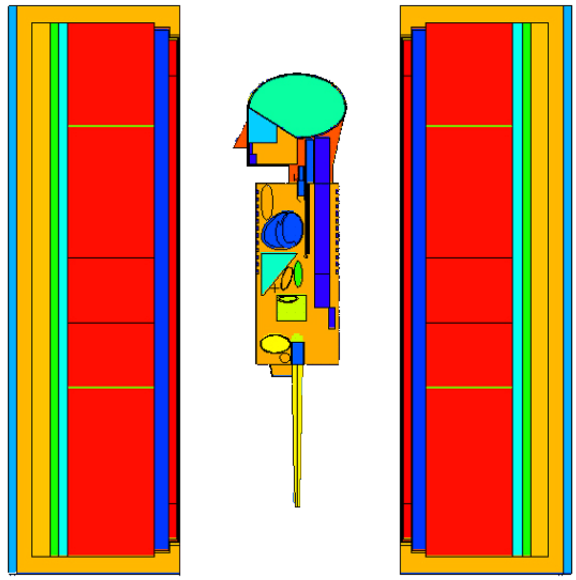

Figure 3. Infant–Philips SKYLight

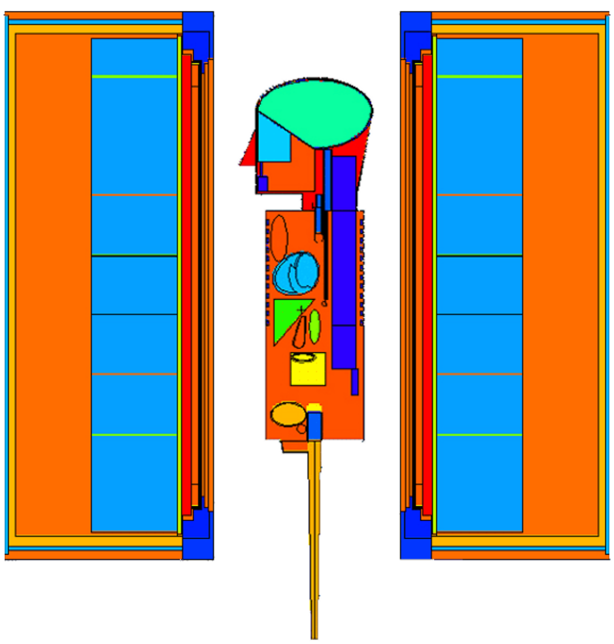

Figure 4. 1-y-old–Siemens e.cam

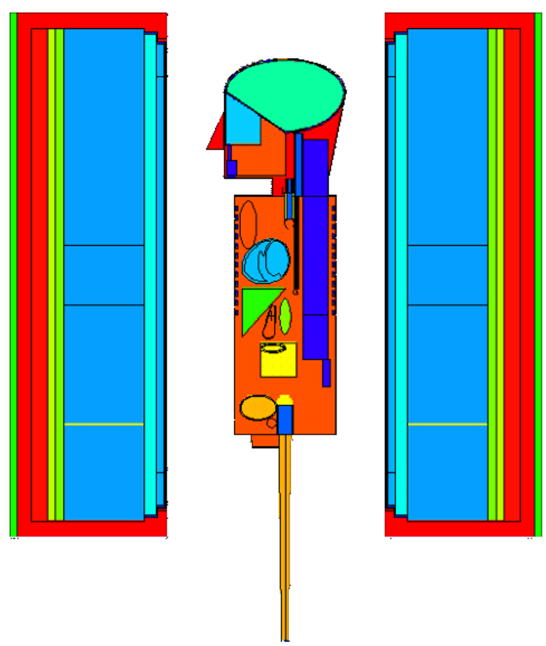

Figure 5. 1-y-old–Philips SKYLight

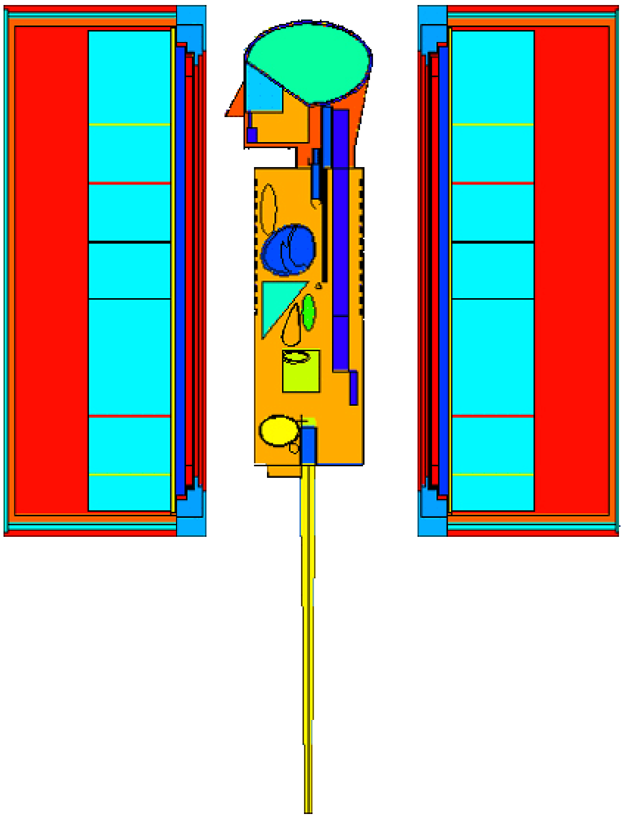

Figure 6. 5-y-old–Siemens e.cam

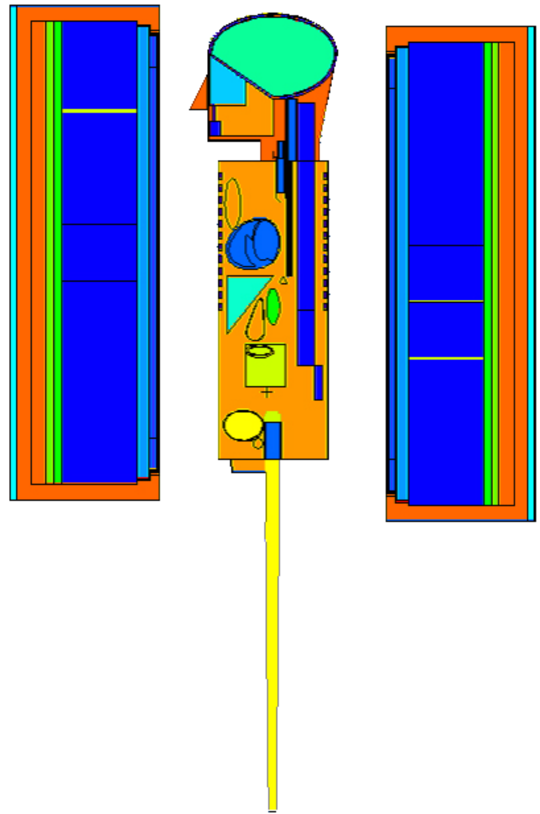

Figure 7. 5-y-old–Philips SKYLight

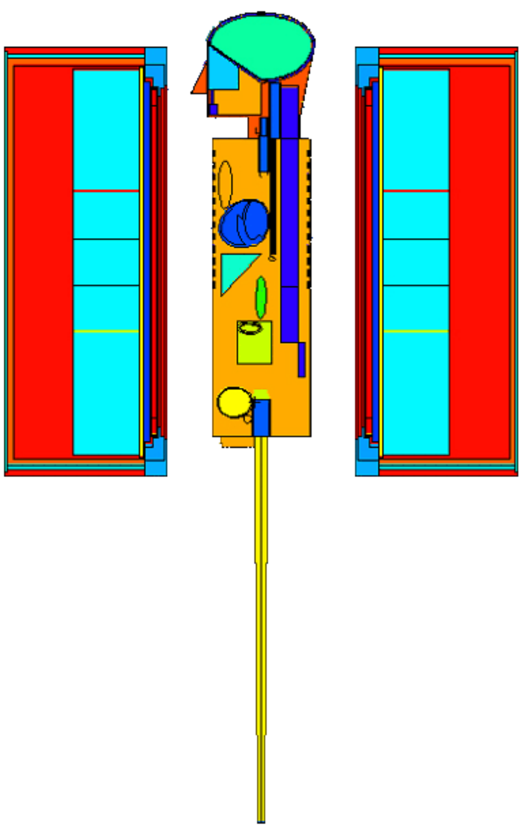

Figure 8. 10-y-old–Siemens e.cam

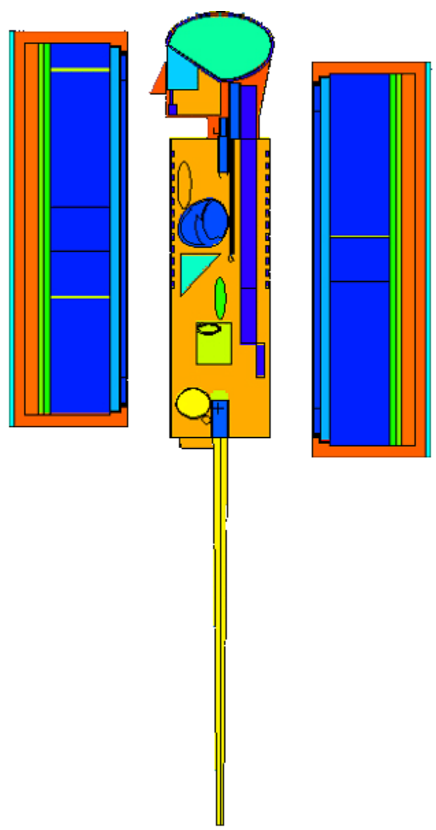

Figure 9. 10-y-old–Philips SKYLight

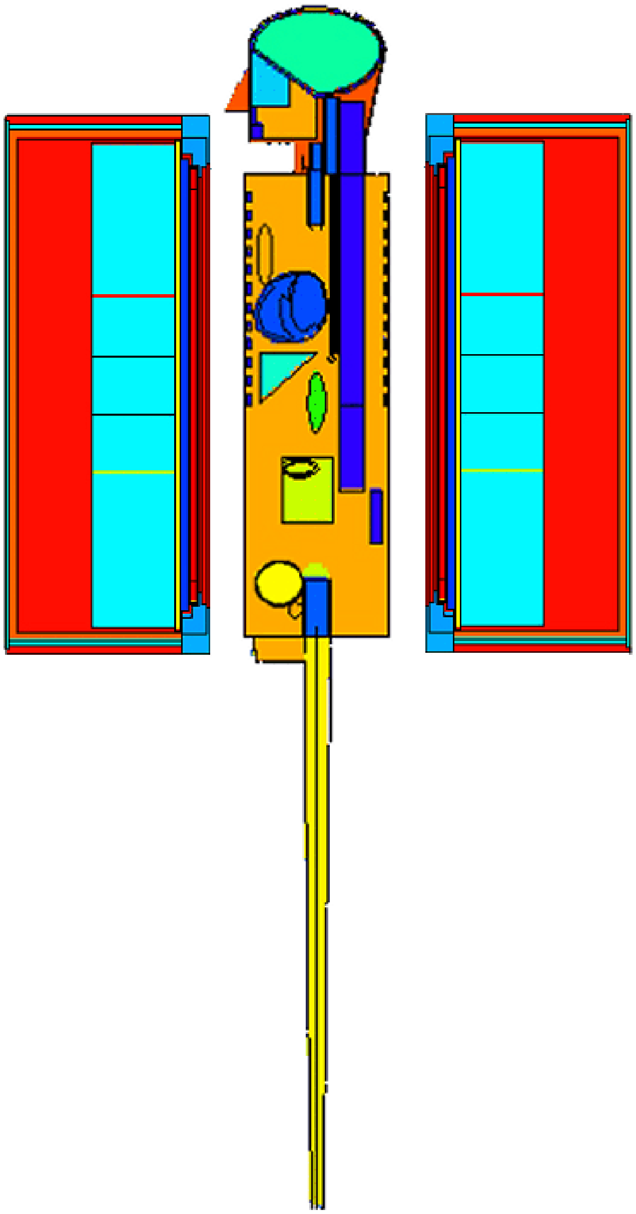

Figure 10. 15-y-old–Siemens e.cam

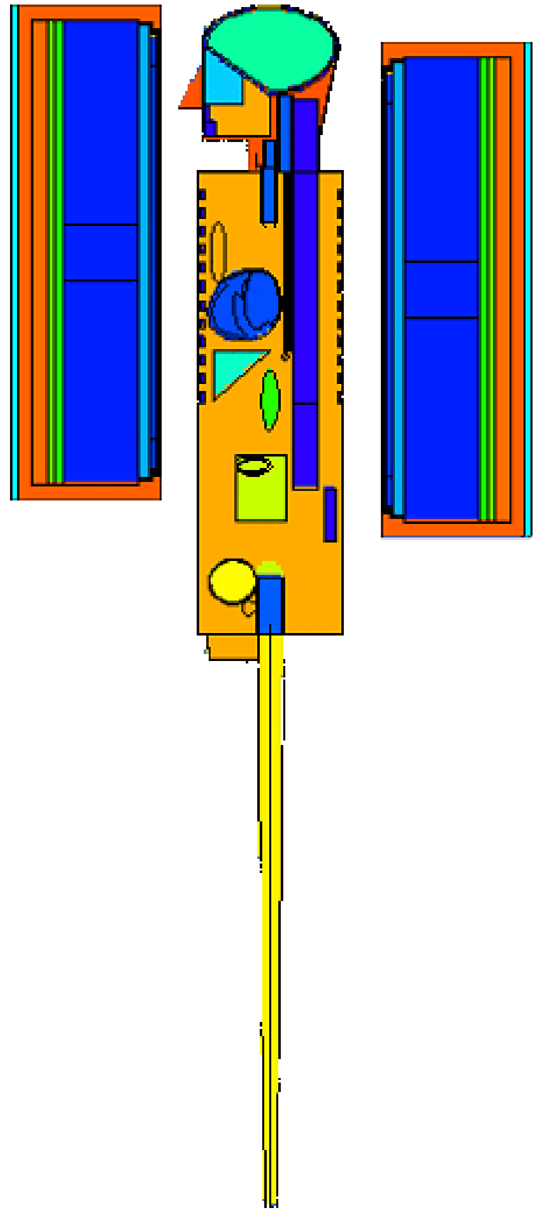

Figure 11. 15-y-old–Philips SKYLight

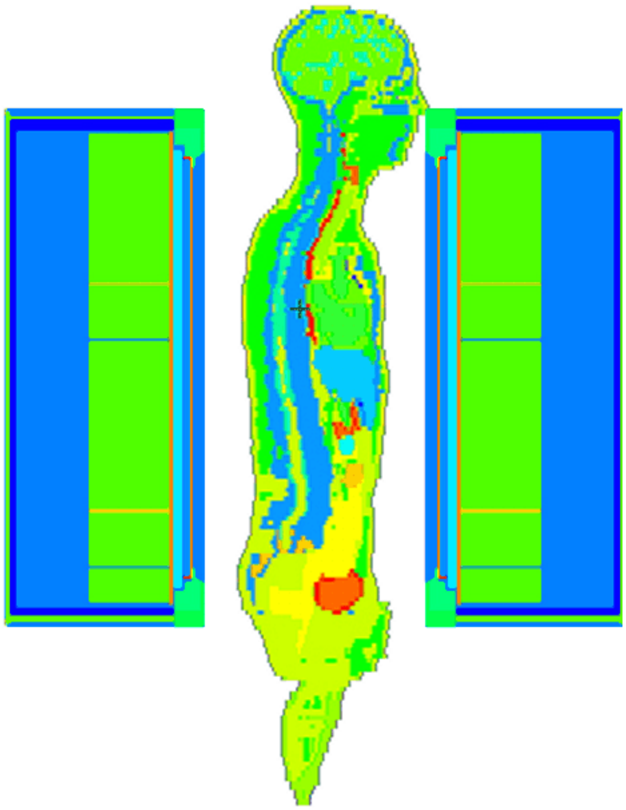

Figure 12. Adult Male–Siemens e.cam

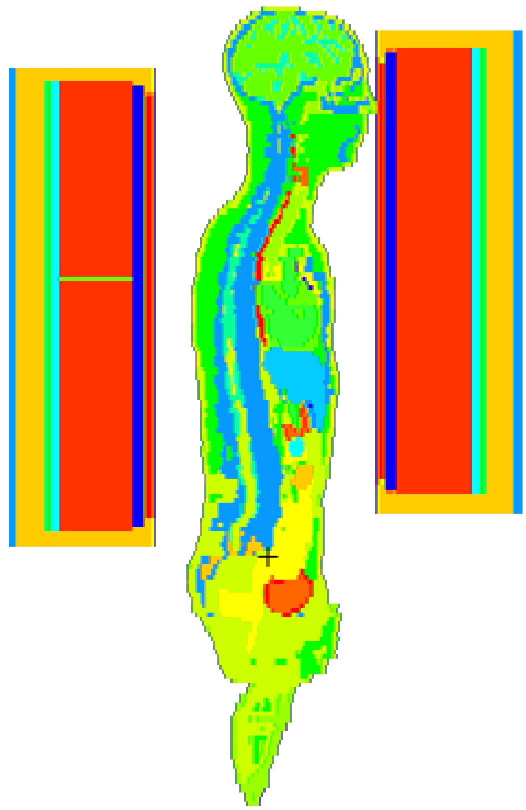

Figure 13. Adult Male–Philips SKYLight

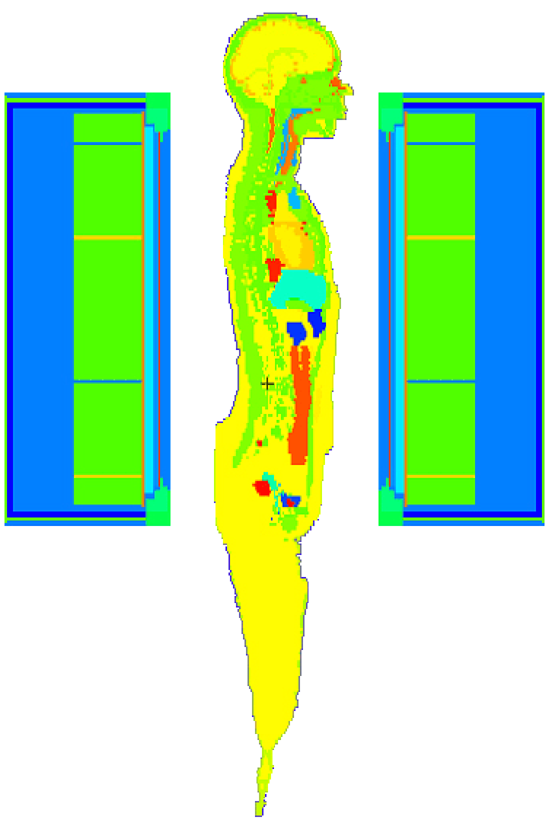

Figure 14. Adult Female–Siemens e.cam

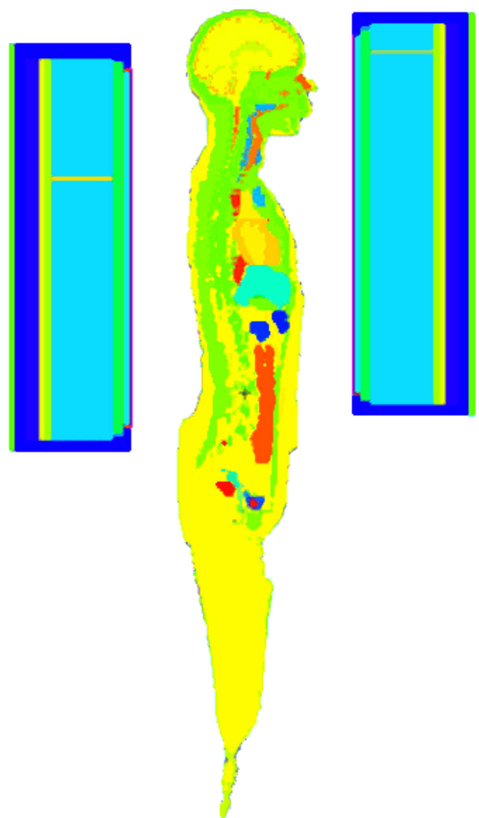

Figure 15. Adult Female–Philips SKYLight

CALIBRATION FACTORS FOR CONVERTING COUNT RATES TO INTAKES

Table 6. Intake of Type M ^{60}Co vs. Count Rate (Bq/kcpm)

Time post intake		Camera					
		Siemens e.cam				Philips SKYLight	
		6 Windows		3 Windows			
d	h	Anterior	Posterior	Anterior	Posterior	Anterior	Posterior
Infant							
0.042	1	169	211	239	295	238	292
0.083	2	172	209	244	293	243	289
0.167	4	179	213	253	298	252	295
0.333	8	193	226	272	316	271	312
0.5	12	209	240	296	337	295	332
1	24	275	300	388	420	387	414
2	48	468	472	659	663	657	652
4	96	854	787	1,199	1,112	1,195	1,090
8	192	1,078	967	1,513	1,369	1,508	1,339
1-y-old							
0.042	1	169	223	236	308	215	277
0.083	2	174	221	243	305	222	276
0.167	4	182	226	253	311	231	282
0.333	8	196	239	273	330	249	299
0.5	12	213	254	297	351	271	318
1	24	284	316	394	436	360	395
2	48	491	496	681	686	623	619
4	96	911	822	1,262	1,142	1,149	1,019
8	192	1,139	994	1,578	1,382	1,434	1,229
5-y-old							
0.042	1	196	296	272	405	246	354
0.083	2	203	294	282	402	256	352
0.167	4	211	300	293	411	268	359
0.333	8	227	318	315	435	289	380
0.5	12	247	338	342	463	315	403
1	24	325	416	449	569	416	496
2	48	540	625	746	857	689	745
4	96	922	960	1,271	1,318	1,154	1,142
8	192	1,114	1,127	1,537	1,550	1,384	1,341
10-y-old							
0.042	1	226	306	313	421	254	358
0.083	2	234	304	324	417	268	356
0.167	4	243	310	337	426	283	365
0.333	8	260	330	359	453	306	388
0.5	12	281	351	389	482	335	415
1	24	367	434	507	596	447	514
2	48	606	659	835	905	733	775
4	96	1,027	1,022	1,413	1,405	1,181	1,182
8	192	1,240	1,204	1,705	1,655	1,397	1,385

Table 6 (continued)

Time post intake		Camera					
		Siemens e.cam				Philips SKYLight	
		6 Windows		3 Windows			
d	h	Anterior	Posterior	Anterior	Posterior	Anterior	Posterior
15-y-old							
0.042	1	255	320	355	444	295	408
0.083	2	264	318	369	442	322	424
0.167	4	273	325	381	451	346	442
0.333	8	288	345	402	478	378	473
0.5	12	309	366	431	508	415	507
1	24	391	443	546	615	541	616
2	48	595	629	829	872	786	812
4	96	890	883	1,237	1,223	1,045	1,008
8	192	1,033	1,009	1,433	1,396	1,169	1,113
Adult male							
0.042	1	265	334	363	458	270	417
0.083	2	274	343	375	471	290	441
0.167	4	284	351	388	482	310	458
0.333	8	302	363	414	499	339	477
0.5	12	326	379	447	521	373	502
1	24	415	447	569	615	496	597
2	48	617	620	847	851	745	790
4	96	877	856	1,205	1,174	1,022	1,002
8	192	1,000	972	1,373	1,334	1,148	1,112
Adult female							
0.042	1	267	339	369	464	314	411
0.083	2	266	351	366	481	330	439
0.167	4	265	365	365	501	337	460
0.333	8	275	383	378	527	351	480
0.5	12	294	403	404	553	380	504
1	24	376	476	516	654	500	599
2	48	587	662	807	907	775	810
4	96	912	919	1,252	1,256	1,120	1,065
8	192	1,067	1,046	1,465	1,429	1,277	1,192

Table 7. Intake of Type S ^{60}Co vs. Count Rate (Bq/kcpm)

Time post intake		Camera					
		Siemens e.cam				Philips SKYLight	
		6 Windows		3 Windows			
d	h	Anterior	Posterior	Anterior	Posterior	Anterior	Posterior
Infant							
0.042	1	168	210	238	294	237	291
0.083	2	171	207	242	290	241	287
0.167	4	176	210	249	294	248	290
0.333	8	187	220	265	308	263	304
0.5	12	202	232	284	325	283	320
1	24	263	287	370	401	368	395
2	48	465	470	653	660	650	649
4	96	939	865	1,318	1,222	1,312	1,195
8	192	1,186	1,058	1,665	1,497	1,655	1,462
1-y-old							
0.042	1	168	222	235	306	214	276
0.083	2	173	220	242	303	221	274
0.167	4	180	223	251	308	229	278
0.333	8	192	235	268	324	244	293
0.5	12	208	248	289	342	264	310
1	24	275	306	381	422	349	382
2	48	482	487	668	674	611	607
4	96	929	837	1,286	1,162	1,169	1,035
8	192	1,142	993	1,582	1,381	1,434	1,225
5-y-old							
0.042	1	195	294	271	403	245	352
0.083	2	201	291	280	399	255	348
0.167	4	209	296	290	405	265	354
0.333	8	222	311	308	426	283	371
0.5	12	240	328	332	450	307	392
1	24	313	400	432	548	402	477
2	48	523	606	722	831	668	721
4	96	910	947	1,255	1,301	1,135	1,125
8	192	1,078	1,089	1,486	1,497	1,333	1,293
10-y-old							
0.042	1	224	304	310	417	252	355
0.083	2	232	300	321	412	266	352
0.167	4	239	305	331	419	280	359
0.333	8	253	321	349	441	300	379
0.5	12	271	340	375	467	326	401
1	24	351	416	484	571	431	492
2	48	582	635	802	872	707	746
4	96	1,008	1,003	1,385	1,378	1,148	1,155
8	192	1,192	1,157	1,638	1,589	1,326	1,324

Table 7 (continued)

Time post intake		Camera					
		Siemens e.cam				Philips SKYLight	
		6 Windows		3 Windows			
d	h	Anterior	Posterior	Anterior	Posterior	Anterior	Posterior
15-y-old							
0.042	1	252	317	351	440	293	404
0.083	2	261	314	364	435	320	420
0.167	4	268	319	373	442	346	438
0.333	8	279	335	389	465	377	467
0.5	12	297	353	414	490	411	497
1	24	372	423	518	588	528	595
2	48	567	601	789	833	754	776
4	96	856	849	1,188	1,175	986	953
8	192	971	949	1,347	1,312	1,074	1,026
Adult male							
0.042	1	260	327	357	448	266	408
0.083	2	268	335	367	460	287	432
0.167	4	275	342	378	469	307	448
0.333	8	290	350	398	480	333	463
0.5	12	311	363	426	498	366	485
1	24	393	424	540	583	481	570
2	48	586	590	806	810	715	751
4	96	839	821	1,151	1,126	967	951
8	192	935	913	1,283	1,252	1,058	1,031
Adult female							
0.042	1	264	334	364	457	311	404
0.083	2	262	345	360	474	326	432
0.167	4	258	358	355	491	332	452
0.333	8	264	373	363	513	343	468
0.5	12	280	389	384	535	368	489
1	24	355	455	487	625	479	573
2	48	558	633	767	868	738	771
4	96	878	886	1,206	1,210	1,063	1,012
8	192	1,007	987	1,382	1,347	1,183	1,108

Table 8. Intake of Type F ^{137}Cs vs. Count Rate (Bq/kcpm)

Time post intake		Camera					
		Siemens e.cam				Philips SKYLight	
		6 Windows		3 Windows			
d	h	Anterior	Posterior	Anterior	Posterior	Anterior	Posterior
Infant							
0.042	1	213	293	361	465	293	395
0.083	2	221	293	374	467	303	394
0.167	4	232	297	393	475	319	400
0.333	8	251	307	423	493	345	413
0.5	12	268	316	452	509	369	425
1	24	315	339	524	549	433	455
2	48	382	372	626	605	524	500
4	96	455	418	737	679	624	561
8	192	551	500	890	813	754	671
1-y-old							
0.042	1	226	336	368	507	286	426
0.083	2	236	337	384	511	299	426
0.167	4	251	343	408	523	318	434
0.333	8	276	357	447	546	351	451
0.5	12	299	370	484	567	382	467
1	24	362	399	577	615	465	505
2	48	455	440	710	680	589	556
4	96	561	501	862	775	730	632
8	192	707	622	1,084	963	921	786
5-y-old							
0.042	1	281	484	448	709	354	614
0.083	2	296	489	473	720	374	620
0.167	4	319	505	508	747	403	639
0.333	8	355	535	565	794	451	676
0.5	12	389	559	617	833	497	707
1	24	476	611	745	915	617	771
2	48	596	670	914	1,006	791	844
4	96	723	749	1,090	1,125	973	941
8	192	876	895	1,317	1,344	1,182	1,124
10-y-old							
0.042	1	360	535	554	778	391	678
0.083	2	384	545	592	795	417	689
0.167	4	417	568	643	832	455	718
0.333	8	467	610	719	896	518	772
0.5	12	510	643	785	948	577	816
1	24	614	710	937	1,050	731	903
2	48	741	779	1,114	1,155	948	991
4	96	866	861	1,289	1,278	1,162	1,096
8	192	1,007	992	1,497	1,472	1,365	1,263

Table 8 (continued)

Time post intake		Camera					
		Siemens e.cam				Philips SKYLight	
		6 Windows		3 Windows			
d	h	Anterior	Posterior	Anterior	Posterior	Anterior	Posterior
15-y-old							
0.042	1	455	602	677	869	440	817
0.083	2	489	616	730	892	466	833
0.167	4	534	645	799	937	510	879
0.333	8	598	694	896	1,013	590	969
0.5	12	651	733	975	1,073	670	1,043
1	24	758	804	1,133	1,184	892	1,188
2	48	859	868	1,277	1,280	1,233	1,320
4	96	942	930	1,394	1,372	1,551	1,432
8	192	1,012	996	1,497	1,469	1,709	1,536
Adult male							
0.042	1	532	696	773	990	411	958
0.083	2	578	728	843	1,039	437	997
0.167	4	641	770	936	1,104	480	1,058
0.333	8	730	826	1,071	1,193	559	1,152
0.5	12	805	869	1,183	1,262	640	1,227
1	24	956	950	1,409	1,388	883	1,374
2	48	1,086	1,019	1,600	1,495	1,311	1,505
4	96	1,179	1,082	1,736	1,589	1,750	1,612
8	192	1,251	1,144	1,841	1,679	1,930	1,707
Adult female							
0.042	1	483	640	714	916	516	865
0.083	2	513	670	762	962	548	912
0.167	4	560	713	834	1,029	603	984
0.333	8	636	776	950	1,128	703	1,094
0.5	12	702	825	1,049	1,205	800	1,185
1	24	840	917	1,255	1,348	1,065	1,361
2	48	969	993	1,441	1,465	1,449	1,511
4	96	1,064	1,057	1,575	1,561	1,783	1,627
8	192	1,130	1,118	1,673	1,651	1,934	1,723

Table 9. Intake of Type F ^{192}Ir vs. Count Rate (Bq/kcpm)

Time post intake		Camera					
		Siemens e.cam				Philips SKYLight	
		6 Windows		3 Windows			
d	h	Anterior	Posterior	Anterior	Posterior	Anterior	Posterior
Infant							
0.042	1	58	84	72	103	75	106
0.083	2	60	84	74	103	77	106
0.167	4	63	86	78	106	80	108
0.333	8	68	91	84	111	87	114
0.5	12	73	95	91	117	94	120
1	24	93	111	115	136	119	139
2	48	139	148	172	181	178	185
4	96	204	197	252	242	260	247
8	192	242	229	298	281	307	287
1-y-old							
0.042	1	62	99	77	121	73	114
0.083	2	64	99	80	122	75	114
0.167	4	68	102	84	125	79	117
0.333	8	74	108	92	133	87	124
0.5	12	81	114	100	140	95	131
1	24	105	132	130	163	124	153
2	48	161	174	199	215	189	201
4	96	240	229	296	282	281	263
8	192	285	264	351	325	334	304
5-y-old							
0.042	1	78	143	97	177	89	158
0.083	2	81	143	101	178	93	159
0.167	4	85	148	106	183	98	164
0.333	8	93	157	117	195	109	174
0.5	12	103	167	128	207	120	184
1	24	134	195	168	242	158	216
2	48	204	254	254	315	242	280
4	96	297	327	370	406	352	361
8	192	351	376	437	467	416	415
10-y-old							
0.042	1	99	158	121	195	100	172
0.083	2	103	158	127	196	105	173
0.167	4	108	163	134	203	112	179
0.333	8	118	174	147	217	124	191
0.5	12	130	185	162	231	138	203
1	24	168	217	211	272	185	240
2	48	248	284	313	356	282	312
4	96	354	366	444	458	405	400
8	192	416	421	522	527	476	459

Table 9 (continued)

Time post intake		Camera					
		Siemens e.cam				Philips SKYLight	
		6 Windows		3 Windows			
d	h	Anterior	Posterior	Anterior	Posterior	Anterior	Posterior
15-y-old							
0.042	1	132	184	168	236	118	222
0.083	2	137	185	175	236	127	231
0.167	4	143	190	183	243	139	244
0.333	8	155	202	198	259	159	267
0.5	12	167	214	214	273	181	290
1	24	208	247	266	316	252	347
2	48	286	311	366	395	386	424
4	96	376	384	480	488	533	496
8	192	434	438	553	555	618	557
Adult male							
0.042	1	141	233	180	290	108	273
0.083	2	145	237	185	296	114	286
0.167	4	151	239	193	298	124	295
0.333	8	164	241	208	302	142	307
0.5	12	179	247	227	310	162	321
1	24	227	275	287	346	229	370
2	48	313	347	394	437	367	460
4	96	404	440	509	553	535	561
8	192	463	505	584	635	627	636
Adult female							
0.042	1	133	194	168	246	130	224
0.083	2	132	202	167	256	135	238
0.167	4	133	211	168	267	141	252
0.333	8	140	224	176	284	153	271
0.5	12	150	236	189	299	170	288
1	24	190	271	240	344	233	339
2	48	275	343	347	435	366	432
4	96	381	431	481	546	531	537
8	192	445	493	563	625	624	613

Table 10. Intake of Type M ^{192}Ir vs. Count Rate (Bq/kcpm)

Time post intake		Camera					
		Siemens e.cam				Philips SKYLight	
		6 Windows		3 Windows			
d	h	Anterior	Posterior	Anterior	Posterior	Anterior	Posterior
Infant							
0.042	1	57	84	71	102	73	105
0.083	2	59	83	73	101	75	103
0.167	4	61	84	75	102	77	105
0.333	8	65	87	80	107	83	109
0.5	12	70	92	87	112	90	115
1	24	93	111	115	136	118	139
2	48	164	174	202	213	208	217
4	96	322	298	396	367	407	372
8	192	414	368	510	453	524	459
1-y-old							
0.042	1	60	97	74	119	70	111
0.083	2	62	96	77	117	73	109
0.167	4	65	97	81	119	76	111
0.333	8	70	102	87	125	82	117
0.5	12	76	107	95	132	89	123
1	24	103	130	127	159	120	149
2	48	181	197	224	242	212	225
4	96	345	316	426	389	400	359
8	192	436	380	538	468	505	431
5-y-old							
0.042	1	73	135	92	167	84	149
0.083	2	77	133	96	165	88	147
0.167	4	80	135	100	168	93	149
0.333	8	86	142	108	177	101	157
0.5	12	94	150	118	187	110	165
1	24	125	179	157	223	147	197
2	48	212	259	264	322	249	285
4	96	368	384	458	475	424	421
8	192	452	451	561	559	516	496
10-y-old							
0.042	1	92	147	115	185	92	159
0.083	2	96	145	121	182	98	157
0.167	4	100	147	126	185	104	160
0.333	8	107	155	135	195	113	169
0.5	12	116	164	146	206	124	179
1	24	152	197	191	248	168	216
2	48	252	287	317	360	279	312
4	96	427	427	536	532	452	455
8	192	521	502	652	626	541	533

Table 10 (continued)

Time post intake		Camera					
		Siemens e.cam				Philips SKYLight	
		6 Windows		3 Windows			
d	h	Anterior	Posterior	Anterior	Posterior	Anterior	Posterior
15-y-old							
0.042	1	117	166	150	213	109	195
0.083	2	123	164	158	210	121	202
0.167	4	128	167	164	213	132	211
0.333	8	134	175	172	224	146	225
0.5	12	143	185	183	236	162	240
1	24	181	218	232	278	215	282
2	48	273	296	350	376	319	352
4	96	405	401	515	507	431	419
8	192	474	461	603	582	493	468
Adult male							
0.042	1	122	175	154	220	99	200
0.083	2	125	180	158	226	106	212
0.167	4	129	183	162	230	114	220
0.333	8	136	186	172	233	127	226
0.5	12	147	191	185	240	141	235
1	24	189	218	238	274	191	270
2	48	281	292	353	366	295	342
4	96	393	396	493	494	412	423
8	192	453	456	568	568	474	476
Adult female							
0.042	1	120	165	152	209	118	182
0.083	2	117	172	148	218	124	197
0.167	4	114	180	144	228	125	207
0.333	8	116	188	147	238	130	215
0.5	12	124	195	156	247	141	224
1	24	160	225	201	284	190	258
2	48	256	300	323	379	304	334
4	96	408	405	515	508	451	427
8	192	488	465	614	583	526	485

Table 11. Intake of Type S ^{192}Ir vs. Count Rate (Bq/kcpm)

Time post intake		Camera					
		Siemens e.cam				Philips SKYLight	
		6 Windows		3 Windows			
d	h	Anterior	Posterior	Anterior	Posterior	Anterior	Posterior
Infant							
0.042	1	57	84	70	102	72	105
0.083	2	58	82	72	101	75	103
0.167	4	60	83	75	102	77	104
0.333	8	65	87	80	106	82	109
0.5	12	70	91	87	112	89	114
1	24	93	111	115	136	118	139
2	48	167	177	206	217	211	221
4	96	343	315	422	388	434	393
8	192	446	391	550	482	565	487
1-y-old							
0.042	1	59	97	74	119	69	111
0.083	2	62	95	77	117	72	109
0.167	4	65	96	80	119	76	111
0.333	8	70	101	87	124	81	116
0.5	12	76	107	94	131	89	122
1	24	102	129	127	159	120	148
2	48	184	199	227	245	214	228
4	96	361	328	446	404	418	372
8	192	459	395	567	486	530	447
5-y-old							
0.042	1	73	134	91	166	83	148
0.083	2	76	132	95	164	88	146
0.167	4	80	134	100	167	92	148
0.333	8	86	141	107	175	100	155
0.5	12	93	148	117	185	109	163
1	24	124	178	155	221	146	196
2	48	213	260	265	322	249	285
4	96	376	389	468	482	431	427
8	192	461	455	572	563	523	499
10-y-old							
0.042	1	91	146	114	183	91	158
0.083	2	96	144	120	180	97	155
0.167	4	100	146	126	183	103	158
0.333	8	106	154	133	193	112	167
0.5	12	114	162	144	204	123	177
1	24	150	195	189	245	166	214
2	48	252	287	317	360	278	312
4	96	435	432	546	539	454	459
8	192	529	506	662	630	541	534

Table 11 (continued)

Time post intake		Camera					
		Siemens e.cam				Philips SKYLight	
		6 Windows		3 Windows			
d	h	Anterior	Posterior	Anterior	Posterior	Anterior	Posterior
15-y-old							
0.042	1	116	165	148	210	109	192
0.083	2	122	162	156	207	120	199
0.167	4	126	164	162	210	131	208
0.333	8	132	173	169	221	145	221
0.5	12	141	182	180	233	160	235
1	24	178	215	228	274	212	276
2	48	272	294	347	373	312	344
4	96	406	400	516	505	418	408
8	192	473	457	601	576	472	450
Adult male							
0.042	1	121	170	152	214	98	194
0.083	2	124	175	155	221	106	206
0.167	4	127	178	159	224	113	214
0.333	8	134	181	168	228	125	220
0.5	12	144	186	182	234	139	228
1	24	186	213	234	267	188	262
2	48	277	287	348	359	287	331
4	96	389	388	488	484	398	407
8	192	445	442	557	551	451	453
Adult female							
0.042	1	119	162	150	205	117	179
0.083	2	116	170	146	215	122	193
0.167	4	113	177	142	224	124	203
0.333	8	114	185	144	234	128	211
0.5	12	122	192	153	243	139	219
1	24	157	220	198	279	186	251
2	48	254	295	320	372	298	325
4	96	410	399	516	500	440	414
8	192	487	454	613	569	507	464

Table 12. Intake of Type M ^{241}Am vs. Count Rate (Bq/kcpm)

Time post intake		Camera			
		Siemens e.cam		Philips SKYLight	
d	h	Anterior	Posterior	Anterior	Posterior
Infant					
0.042	1	310	597	355	675
0.083	2	323	586	370	661
0.167	4	337	592	386	666
0.333	8	362	614	414	691
0.5	12	393	638	449	717
1	24	524	749	597	841
2	48	926	1,116	1,052	1,251
4	96	1,767	1,773	2,006	1,988
8	192	2,144	2,050	2,433	2,299
1-y-old					
0.042	1	352	846	375	887
0.083	2	372	829	397	870
0.167	4	393	838	420	880
0.333	8	427	872	457	917
0.5	12	471	906	504	954
1	24	645	1,049	691	1,105
2	48	1,162	1,474	1,242	1,549
4	96	2,206	2,121	2,343	2,215
8	192	2,673	2,379	2,833	2,482
5-y-old					
0.042	1	467	1,302	486	1,319
0.083	2	497	1,281	519	1,295
0.167	4	527	1,300	553	1,313
0.333	8	574	1,358	605	1,373
0.5	12	633	1,412	669	1,427
1	24	863	1,609	919	1,627
2	48	1,492	2,119	1,588	2,146
4	96	2,574	2,786	2,695	2,826
8	192	3,015	3,059	3,137	3,105
10-y-old					
0.042	1	685	1,593	580	1,577
0.083	2	739	1,563	632	1,552
0.167	4	782	1,587	680	1,580
0.333	8	838	1,666	747	1,665
0.5	12	913	1,735	829	1,741
1	24	1,216	1,980	1,148	1,995
2	48	2,008	2,589	1,946	2,590
4	96	3,241	3,362	3,110	3,312
8	192	3,728	3,680	3,554	3,612

Table 12 (continued)

Time post intake		Camera			
		Siemens e.cam		Philips SKYLight	
d	h	Anterior	Posterior	Anterior	Posterior
15-y-old					
0.042	1	1,111	2,064	703	2,165
0.083	2	1,204	2,035	780	2,245
0.167	4	1,262	2,070	861	2,336
0.333	8	1,317	2,175	971	2,464
0.5	12	1,408	2,264	1,090	2,578
1	24	1,781	2,533	1,503	2,865
2	48	2,619	3,095	2,375	3,226
4	96	3,622	3,705	3,366	3,498
8	192	4,004	3,982	3,733	3,684
Adult male					
0.042	1	1,193	2,363	659	2,439
0.083	2	1,184	2,436	707	2,585
0.167	4	1,184	2,428	762	2,641
0.333	8	1,246	2,379	854	2,645
0.5	12	1,355	2,391	963	2,693
1	24	1,780	2,611	1,354	2,952
2	48	2,623	3,274	2,213	3,488
4	96	3,461	4,107	3,225	4,025
8	192	3,756	4,478	3,588	4,307
Adult female					
0.042	1	1,136	1,907	821	1,888
0.083	2	1,057	2,027	847	2,072
0.167	4	985	2,125	847	2,197
0.333	8	976	2,185	880	2,250
0.5	12	1,034	2,227	965	2,293
1	24	1,352	2,425	1,348	2,488
2	48	2,226	2,980	2,281	2,959
4	96	3,586	3,673	3,475	3,487
8	192	4,103	3,983	3,897	3,748