MEDICAL PHYSICS PUBLISHING

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Chapter 20

Experiences with Early Emergency Response and Rules of Thumb

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Introduction

This chapter will present some basic principles of responding to attacks from radioactivity-dispersing devices (RDDs) or nuclear weapons, as learned and adapted from experiences in:

(a) evaluating and treating at the University of Pittsburgh Medical Center's Radiation Medicine Department, and elsewhere, dozens of cases of external radiation exposure, and the human intake and contamination from radionuclides over the range of radiotoxicities; and

(b) training responders to understand radiation measurements and risk and to utilize radiation monitoring instruments to minimize radiation exposure and public panic following a nuclear attack.

The experience presented in this chapter is derived mainly from accident cases that occurred decades ago. This type of experience, which provides lessons applicable to emergency response today, has not been available to most health physicists because the kinds of radionuclide processing and experimental work performed in the first three decades after the discovery of fission have not been conducted in the United States for several decades. Lessons learned from these selected cases, as they would apply to triage or emergency actions after terrorist attack, are summarized after each scenario to illustrate important concepts of emergency preparedness and response.

Accidental High Radiation Exposures

Van de Graaff Accident Involving Amputation of Forearms and Legs, with Successful Bone Marrow Transplant

Three workers were accidentally irradiated at the Van de Graaff (VDG) accelerator facility at the former Gulf Oil Corporation Research Laboratory in Pittsburgh on 4 October 1967. The experienced accelerator operator was exposed to intense bremmstrahlung radiation while unscrewing target cooling tubes, unaware that multiple safety interlocks had failed to operate. A phantom was positioned to mock up the exposure, with thermoluminescence, ionization chamber and film dosimeters positioned to estimate the complete exposure distribution. The exposure distribution was normalized to the reading of a film badge worn by the operator at his waist. A worker who was next to the operator during the exposure but did not have his hands and feet in the beam and a third worker who was more distant and present for a shorter time also had worn film badges at the waist. The film

badge readings had been interpreted as 300 R for the first two individuals and 100 R for the third by Landauer and Company. A visit to Landauer with an independent densitometer confirmed, on the insensitive films of each packet as retrieved by Robert S. Landauer, Jr., that the exposures at the waist were indeed 300, 300, and 100 R, respectively, within about 20%.

With the distribution normalized to the waist reading, the operator was estimated to have received a mean marrow dose of 600 rad, with major weighting by the estimated 6,000 rad to the forearms and about 2,000 to 3,000 rad to the lower legs. The close co-worker was estimated to have an average bone marrow dose of only 300 rad. At the plenary session of the 1969 Health Physics Society meeting, Wald (1969) reported that the relative doses for the two individuals, as estimated by dicentric and ring chromosomes, was also in the ratio of 600 to 300 rad.

Well before the confirming dosimetry had been completed, the need to place the two individuals in special care in a germ-protected hospital environment was determined from the prodromal symptoms of early nausea and vomiting and blood count changes. For the VDG operator, arrangements were made for the performance of a bone marrow transplant from the operator's identical twin by E. Donnal Thomas, the developer of the technique, on the ninth postexposure day. As a result, the operator's granulocyte and lymphocyte counts, which had been dropping rapidly before the transplant, began to return to normal by the 19th postexposure day, while the close coworker's white count continued to drop to a very low level until the fourth postexposure week.

Despite the successful transplant, the operator's severely injured forearms and lower legs required sequential amputations of the devitalized tissues, which resulted from direct tissue damage as well as their damaged blood supply. The operator led an active life nevertheless until he died from a coronary occlusion 18 y later, which ironically was 2 y later than his twin brother's death of the same cause.

Further details of this interesting case can be examined in Wald et al. (1968a, 1969a), Schenk and Gilberti (1970), Thomas et al. (1971), Gilberti (1980), and Gilberti and Wald (1991). There are lessons to be learned regarding radiation protection practice as well as medical response from this accident.

Lessons Learned

1. Nonuniform exposure that results from shielding just a portion of the body by rapid action can effectively reduce the injury and death from a short-term, high external radiation exposure.
2. While the patients in this case felt relatively well for about the first 2 d after initial nausea, medical knowledge of prodromal symptoms of the acute radiation syndrome was necessary to initiate proper care and keep them hospitalized (Wald 1969b). Medical personnel who are expected to care for seriously exposed persons must have special advanced training (Wald 1969b; Mettler and Upton 1995).

3. Radiation monitoring instruments capable of measuring high levels without saturating must be kept tested and calibrated and carried by anyone entering potentially high radiation areas.

Accidental Intakes of Radioactive Material

Glovebox Explosion Involving ^{239}Pu and ^{241}Am Oxide Contamination

Initial Scenario. This case, an accident in a plutonium fuel fabrication plant, occurred on 17 January 1966, soon after the opening of the University of Pittsburgh whole-body counter and bioassay laboratory, which supported the Radiation Medicine Department of Presbyterian-University Hospital. Only large NaI detectors were in operation for the evaluating of intakes from higher-energy gamma emitters. Fortunately, however, two 2-inch-diameter × 1-mm NaI crystals mounted on photomultiplier tubes had been purchased and were delivered just before the incident. Despite admonitions that our laboratory was not equipped to evaluate this case, the case was managed well medically and dosimetrically with this simple equipment. This case shows the feasibility of emergency management of internal exposure assessment and treatment with relatively simple equipment and a physician-health physics team prepared in the relevant medical and physical sciences (Brodsky et al. 1968). However, the case also shows difficulties that were encountered without prior funding to prepare our own laboratory to perform urine, fecal, and other sample radiochemical analyses at this time. Administrative and management lessons learned will be summarized later in this chapter.

At 2:05 p.m., Monday, 17 January 1966, an explosion occurred in a glovebox when a technician attempted to ignite a propane torch. The torch had apparently leaked after a new cylinder was attached. The explosion blew out the gloves and knocked the operator to the floor. Within seconds the operator proceeded to the change room, and within 1 min the plant evacuation alarm was sounded.

Hot gases from the open glove ports had singed the operator's eyebrows and produced minor first-degree facial burns. His face, hair and chest were contaminated with alpha activity up to several hundred thousand disintegrations per minute per 100 cm^2. Nose swipes read up to 100,000 counts per minute. The worker's clothing was removed and he was showered despite the high level of head contamination and absent body contamination due to protection from his clothing. This redistributed the contamination to otherwise clean areas.

Twenty-four-hour urine samples were taken on all persons involved in the incident, and fecal samples were also collected from the glovebox operator. The glovebox operator showered at the hospital until all external alpha contamination had been removed, except for one spot reading 1,200 counts per minute on the right front chest. His nasal contamination was reduced below 1,000 counts per minute per smear by irrigation with water.

Air samples at the plant indicated alpha air concentrations of up to 10^{-7} μCi/mL in the room where the incident had occurred averaged over about 20 min after the accident. (Air concentrations ["MPCs" at that time (ICRP 1960)] were limited for worker exposure over 50 y to 2×10^{-12} μCi/mL for compounds of plutonium soluble in lung fluid, based on bone dose, and 4×10^{-11} μCi/mL for insoluble plutonium.) Corresponding limits for americium were 6×10^{-12} μCi/mL and 1×10^{-10} μCi/mL, respectively (ICRP 1960). Floor contamination levels in the vicinity of the incident were up to 300,000 counts per minute per 100 cm^2 (the same order of magnitude as that on the skin of the operator), and contamination was spread throughout the entire plant. However, the glovebox operator involved had the highest contamination and was the only one who was found later to have measurable internal activity.

Patient Evaluation and Medical Management. On the day after the accident, the company health physicist asked whether we could evaluate and manage the case. We had recently obtained a thin-window, 2-inch-diameter × 1-mm NaI detector with a 0.005-inch-thick aluminum window that would pass 96% of the 17-keV plutonium and americium L x-ray spectra. We had been told that this detector would not have sufficient detection capability and that we should send the patient across the country to a specific national laboratory. Knowing our statistics, we knew that if we had the patient hospitalized for observation we could take many measurements with a smaller detector to obtain the same detection capability, and also have better spatial resolution as we moved the detector to different locations on the patient's body. We were prepared to make measurements around the clock as necessary to avoid sending this patient far from home. We decided to accept the case and prepare our laboratory for the evaluation.

Details of this case and a running account of the interpreted internal plutonium and americium body content and distribution are presented in Brodsky et al. (1968). Only some highlights indicating lessons applicable to responding to intakes from terrorist attacks are presented here.

One of the valuable operating decisions was to use the multichannel analyzer in two halves, so that spectra could be overlapped and compared on the same scale. This would be easy with modern equipment. It is important to realize that the evaluation of each human case is similar to a detective investigation; visual examination of all evidence is important and cannot be replaced only by preprogrammed calculations. Many photographs were taken of overlapped oscilloscope spectral patterns, which we pasted into notebooks in order of time taken with notations. Spectra from the lung were calibrated to an approximate absolute scale using a cylindrical plastic bottle filled with a 1-L solution in which 1 μCi of ^{239}Pu and 0.044 μCi of ^{241}Am were dissolved.

Fig. 20.1 shows a 20-min spectrum over the front right chest (top) and viewed through the body with the patient prone on a cloth cot (bottom). The relatively high 17/60 keV peak ratio from the front, with the much lower ratio viewed from the back, enabled the detection of a new speck of contamination on the chest that increased chest count by a factor of 1,000. This speck of contamination occurred after the first DTPA treatment on d 5. Comparisons of the standard solution with the undershirt, after the shirt's removal, and other measurements showed there was a loosening of a speck of contamination on the scalp and
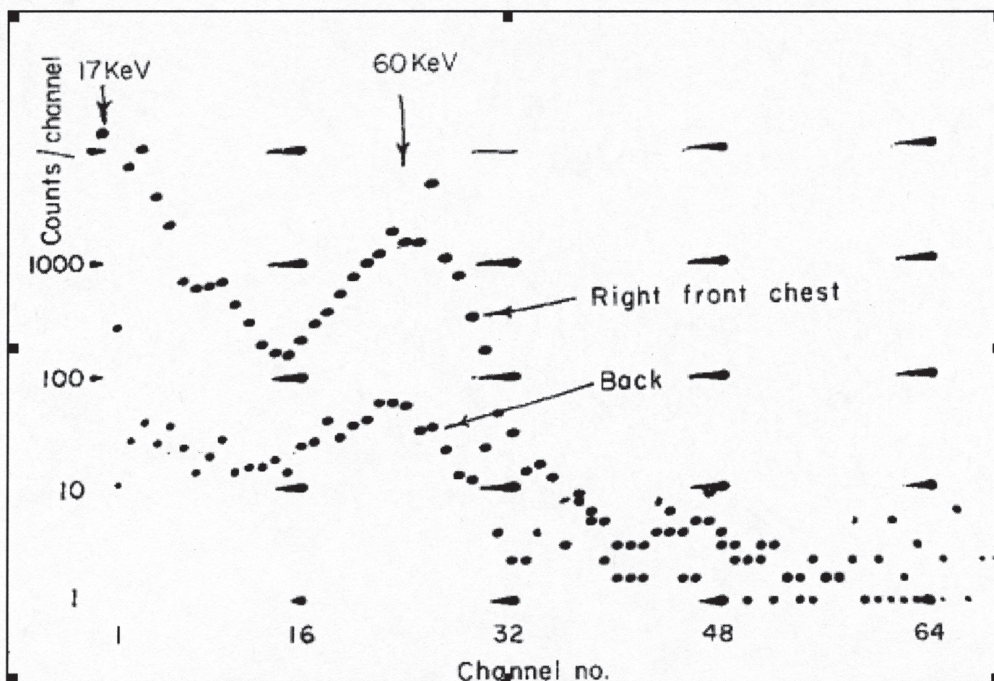
Fig. 20.1. Spectra of contamination found on chest, d 5 postaccident, as viewed by 2-inch diameter × 1-mm-thick NaI crystal detector from front right chest (top) and through back (bottom). From Brodsky et al. (1968), with permission.

attachment to the front of the patient's undershirt when he pulled the shirt over his head that morning.

Fig. 20.2 shows a 20-min spectrum with the detector against the chest of the patient at 18 h postaccident compared to the spectrum with a control subject. The internal lung burden is clearly measurable with this detector setup.

Early counts indicated that if the inhaled material was evaluated as ^{239}Pu there could be about 0.4 µCi in the lungs. This amount would be about 10 times the "maximum permissible body burden" of ICRP (1960) and would indicate, if translocated to bone, the delivery of an average bone dose rate of about 300 rem per year. This finding was sufficient reason for the initiation of chelation therapy.

By d 4 postaccident, information from fecal and smear analyses in our laboratory had indicated that the dust inhaled was predominantly ^{241}Am. Also, isotopic analysis later confirmed that the contamination was more than 85% ^{241}Am. Evaluations of lung burden using the 60-keV peak then ranged from 0.021 µCi ^{241}Am after 1 d (which compares with the then-recommended limit of 0.05 µCi ^{241}Am that would produce a projected bone dose equivalent to about 30 rem per year [ICRP 1960]) to 0.003 µCi by d 7, after 1-g DTPA treatments on each of d 5, 6, and 7. With an effective half-life of 140 y as assumed in ICRP (1960), once in bone the 50-y bone dose for a young person who incorporated about 0.02
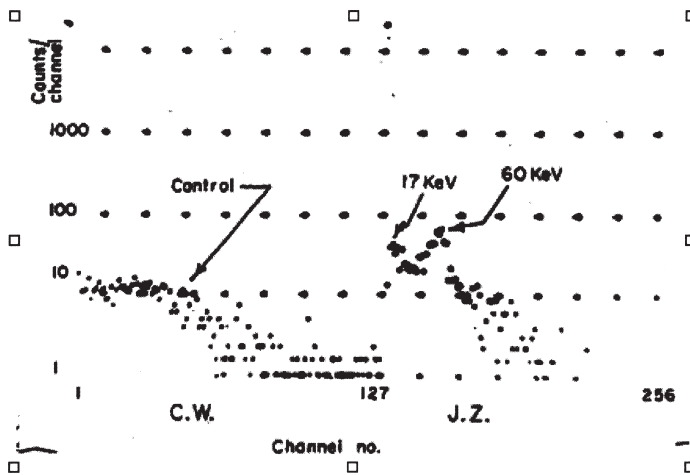
Fig. 20.2. Comparison of spectra of uncontaminated employee (control) with spectrum of exposed technician 18 h postaccident. Vertical counts scale is logarithmic. Note that the 17-KeV x-ray peak is only in the third channel but is clearly significant compared to control counts in that region. Urgency in managing the patient prevented stretching the spectrum after a student had reduced scale and calibrated the set-up. This turned out to be fortunate, since the multichannel analyzer later failed on the upper channels during the evaluation. Adapted from Brodsky et al. (1968), with permission.

μCi ^{241}Am into bone could be about 660 rem. A later case of pure americium inhalation showed that the effective half-life in bone is more likely to be about 20 y (Rosen et al. 1980). (Present estimates indicate that any of these total bone doses from the americium remaining after treatment would be well below the median threshold dose for lethality for Class W weapons-grade plutonium of 19 Gy [1,900 rad, or 22,800 rem using the median RBE of 12; Scott and Peterson 2003].)

The point should be made here that, although ICRP models of bone metabolism have been revised drastically since 1960 to recognize that the target tissues in bone to produce osteosarcoma are thin layers of cells on endosteal (and periosteal) surfaces (ICRP 1979), the net result of permissible intake limit calculations must place these bone-seeking elements in the proper radiotoxicity category to agree with the already-determined experimental ratios of activity required to produce bone sarcoma in animals. No bone sarcomas have yet been attributable to these nuclides in humans. Thus, the resulting permissible intake limits of ICRP (1960) and ICRP (1979) for plutonium are effectively the same (Brodsky 1992). Further, the models of the ICRP Publication 30 report (ICRP 1979) are more applicable to deterministic effects than later ICRP models (Scott and Peterson 2003).

Excretion analyses showed a high initial fecal excretion of 36,000 alpha disintegrations per minute (dpm) of ^{241}Am and about 57 dpm of ^{239}Pu on the first day, with a negligible amount in urine. The fecal excretion dropped sharply on the second and third days, as would be expected from the lung models of ICRP, but then increased sharply following the

DTPA administrations. This striking effect of the DTPA was somewhat surprising, since expert opinion at that time was that both the plutonium and americium oxides in lung would not readily be removed by these chelation treatments. Later cases validated that americium oxides in soft tissues can be much more easily mobilized by DTPA than plutonium oxides.

The initial amount of fecal excretion (0.016 μCi) and the remaining lung burden of 0.02 μCi after d 1 were considered to be in agreement within the range of ICRP models at that time. This provided further confidence that the evaluated burdens were of the correct order of magnitude. Within 22 d, the [241]Am burden fell below 0.002 μCi. The patient was followed for 4 mo with no further appearance of detectable [241]Am.

Lessons Learned

The following lessons are applicable to responding to attacks involving internal radiation exposure of responders or members of the public:

1. Samples of contamination in the vicinity of exposed persons should be carefully collected and preserved for use in the interpretation of human intakes.
2. Simple and inexpensive detectors and equipment can be adapted for use with multichannel analyzers, collimators to reduce background, and with prior calibration, for use in triage (and even later follow-up) of persons exposed to plutonium and/or transplutonium elements under emergency conditions. Larger detectors, or germanium detectors providing sharper resolution of photopeaks (Kramer et al. 2003), are more expensive and not as adaptable to determine relative spatial distributions of radioactivity in the body. Although a total count in a certain time might increase as the area of the detector (for given thickness), the same total count obtained from multiple 20-min measurements with a smaller area detector can also provide the same (or greater) detection capability and more information on spatial distribution, since the minimum detectable amount (MDA) (for paired 20-min background counts) may be estimated by this formula (Brodsky 1986):

$$MDA = (4.65\ S_b + 3)/KT,$$

where

S_b = standard deviation of total blank count (e.g., for total of 20 min)
K = detector calibration factor (e.g., counts per minute per microcurie spread through a phantom lung (Kramer et al. 2003), and
T = total counting time in minutes, for each of the patient counts and for the paired background count.

This formula for paired measurements was one of those recommended as a general standard (Health Physics Society 1996) for comparing detection capabilities for different measuring systems, although longer background counts might statistically provide a slightly lower MDA. However, for emergency use, this simple formula and a paired

background taken close in time to the patient measurement can be more practicable and are not subject to the longer-term variations of control counts that might occur in the presence of changing amounts of environmental contamination.

The results of this case showed that multiple measurements and examination of Pu-Am spectra with 20-min counts of a 2-inch × 1-mm NaI detector against the chest, calibrated with a bottle phantom containing known quantities of plutonium and americium, can allow the detection of about 0.002 μCi of ^{241}Am, or 0.03 μCi of ^{239}Pu in the human lung. (The maximum permissible body burden for lifetime exposure of workers at that time was 0.05 μCi of ^{241}Am or 0.04 μCi of ^{239}Pu [ICRP 1960].) Furthermore, with 200-min counts (preferably 10 20-min counts) the detection limits can be reduced to about 0.0007 μCi of ^{241}Am or 0.01 μCi ^{239}Pu (ICRP 1960).

These values for plutonium compared with a detection limit of 0.016 μCi of ^{239}Pu in dogs, using a 52-detector arrangement for total body counting (Swinth and Griffin 1970). Toohey et al. (1983), using large NaI crystals and anatomically humanoid phantoms, reported limits of detection (at 95% confidence) for activity in the lungs of an individual with average chest wall thickness (28 mm) of about 0.035 μCi of pure ^{239}Pu and less than 0.0003 μCi of ^{241}Am. The isotopic ratios must be known for a mixture, since the relative x-ray emission for ^{240}Pu per alpha decay is over twice that of ^{239}Pu, and that of ^{241}Am is almost 10 times that of ^{239}Pu. If ^{241}Am is in abundance of at least 0.01% by mass, it can be used as a tracer for plutonium when isotopic ratios of the nuclides are obtained by alpha spectroscopy of samples taken soon after an exposure (Toohey et al. 1983).

These detection levels were obtained within a special steel room that reduced background radiation in the region of interest, and with the patient on a cloth cot that had been checked for background radioactivity. However, under emergency conditions, a thin NaI detector could be contained within a lead or steel shield collimator in the field to obtain similar detection levels, since, for a control subject background count, the 60-keV and 17-keV spectral regions for americium, and the 17-keV region alone for plutonium, would be relatively flat (see Fig. 20.2).

Although more precise measurements today require corrections for chest wall thickness (Kramer et al. 2003), auxiliary studies (Bukovitz et al. 1969; Bukovitz and Brodsky 1970) with human cadavers showed that, if the fraction of americium is determined and used to assist in interpreting plutonium quantities, the 60-keV gammas of americium originating throughout the lung scatter, even in the backward directions, so that most of them stay within the region of interest around the 60-keV peak as they interact with the detector. Compton scattering does not seriously deplete the energies of first- or second-scattered quanta at 60 keV. Also, the photoelectric absorption of rib bone is still not high enough to greatly shield the detector from material in the lung. Surprisingly, some measurements in the 60-keV region, for americium sources in tubes in air simulating dispersal in a lung, gave a ratio of 1.02 times the count of an equivalent total concentration in the lung of the cadaver (Bukovitz and Brodsky 1970).

3. Predetermined models and algorithms for estimating internal dose should allow flexibility of input parameters that might not exactly follow those used in ICRP calculations of intake limits. Models for dose calculation should be adapted to the rates of translocation, distribution, and excretion determined from each patient's measurements.

4. Persons by quick action (or breathing through four folds of handkerchief) can escape air concentrations that are more than 10,000 times higher than the permissible limits for routine occupational exposure to the most radiotoxic nuclides, and have nasal contamination on the order of 100,000 alpha dpm per smear (Brodsky and Lessard 1988), and still not have high expectation of harmful effects—particularly if managed by appropriately informed physicians and health physicists.

Glovebox Explosion Involving Nitrates of ^{239}Pu and ^{241}Am

Initial Scenario. Another accidental exposure evaluated in 1966 involved a glovebox explosion that released compounds of plutonium and americium that were more soluble in lung fluids (Wald et al. 1968). This case exemplifies the uncertainties in initial information that are sometimes presented to those managing an emergency evaluation.

In this case, the external contamination was spectacular. Alpha count rates on the patient by Eberline PAC 3G and PAC ISA proportional counters were up to 10^6 counts per minute, corrected to about 50% geometry, and as high as we could read. Removable contamination was all over the body, with maxima of 10,000 alpha counts per minute on the face and 20,000 on the legs, as measured on smears of approximately 100 cm^2 areas placed in a gas-flow proportional counter at about 50% efficiency. (Skrable et al. [2002] have suggested an action level for wearing personal air samplers of 6,000 alpha dpm per 100 cm^2 on surfaces in the workplace.) These measurements were made after the patient had been decontaminated at the site, had undergone further decontamination at the local hospital, and was finally brought to us. We thus needed to find better ways to decontaminate his skin. His external contamination was subsequently treated further for a period of 12 h. Phisohex and other agents were not effective, but the contamination was finally reduced very sharply with the use of a chelating solution developed by Dr. Jack Schubert of our faculty. Schubert's solution was designed to remove the plutonium and americium from skin without causing skin damage. The formulation was reported in our paper and is given in Table 20.1.

This patient had the additional complication of wounds: two cuts on the right hand that were sutured at the first medical treatment site. The wounds served as a residual depot of the radioactive material. They were small lacerations of the fourth and fifth fingers. The scar tissue was subsequently excised because there was continued high activity in the area, and a radioautograph of the histological tissue section (shown in Wald et al. 1968) demonstrated a very diffuse distribution of the material.

Our initial *in vivo* measurements were made 1 d after the incident. The data are presented in Table 20.2. In this case, we were initially in error on the low side in estimating

Table 20.1. "Schubert's Solution" for skin decontamination.[a]

Tartaric acid	3.0 g L^{-1}	(0.2 M)[b]
Citric acid	4.2	(0.2 M)[b]
Disodium DTPA or EDTA	8.0	(0.2 M)[b]
Calcium chloride	2.2	(0.3 M)[b]

[a]Adapted from Wald et al. (1968).
[b]Adjusted to pH = 7 with concentrated NaOH.

only 0.4 µCi of plutonium. We did not have any idea at the time of the first measurements of the ratio of Pu:Am; we assumed it to be 1:1 in activity, based on information supplied by the company involved in the incident. It actually turned out that the initial body deposition would have been on the order of 2 µCi of combined alpha activity of ^{239}Pu and ^{241}Am. The correct ratio of Pu:Am was about 9:1 (the ratio is backward in our publication), as determined from an air sample taken at the time of the incident. Thus, the initial estimate, based primarily on the 60-keV peak of americium, was multiplied by 5 to obtain an initial estimate of 2 µCi of plutonium plus americium alpha activity. This initial burden of these two alpha emitters was projected to produce, after total translocation from the lung, an initial bone dose of about 1,500 rem per year (ICRP 1960). Thus, DTPA treatment was determined to be medically indicated, if effective. The next measurements presented are at 60 d and over the time period from 70 to 130 d, during which the body content fell gradually. Repeated DTPA treatments were given during this time.

The urinary excretion data are shown in Fig. 20.3. The excretion was influenced by the intake of a more soluble plutonium compound than that encountered in the first case above, including that localized in the lungs and that in the wounds. The americium curve is similar to that for plutonium over the time span indicated. The influence of chelation therapy is evident, on dates indicated by the upward-pointing arrows in Fig. 20.3. The urinary data indicated that there was still a residual body burden after 130 d and treatment with a total of 11 g of DTPA (Table 20.2). The lung component of this body burden could still be

Table 20.2. Sequential estimates of body burden for intake of Pu-Am acid solution.[a]

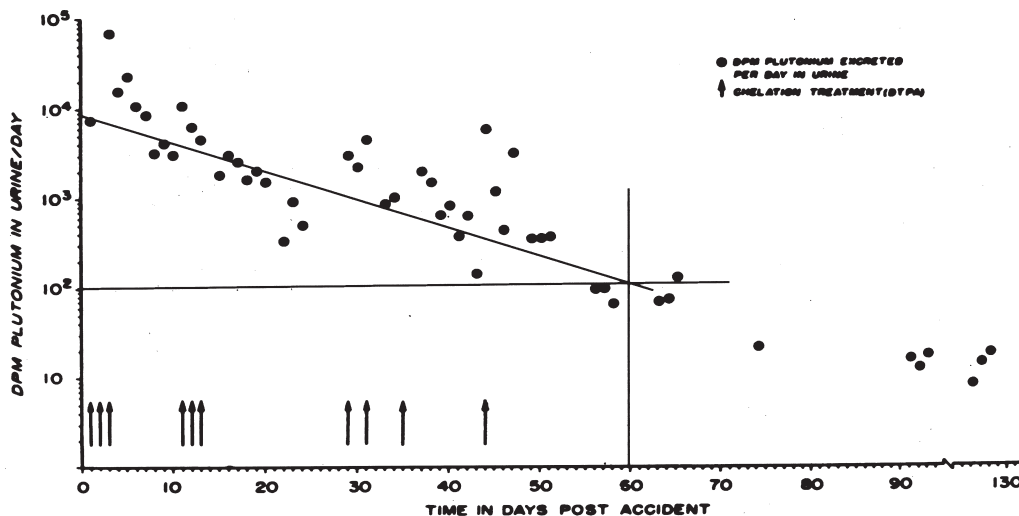| Time postincident	Total body burden estimated from ^{241}Am peak		Systemic burden estimated from urinalysis	
1 d	0.4 µCi ^{239}Pu + ^{241}Am (should have been 2 µCi)		Only rough checks available	
60 d (after 10 g DTPA over 3 mo)	0.3 µCi	(x or/ 2)	0.5 µCi	(x or/ 2)
70–130 d (after 11 g DTPA)	0.2 µCi	(x or/ 2)	0.13 µCi	(x or/ 2)

[a] Adapted from Wald et al. (1968).

Fig. 20.3. Urinary excretion (alpha disintegrations per minute excreted per day) after single exposure to inhalation and injection of Pu-Am acid solution, with DTPA treatments indicated by upward-pointing arrows. These are the data, along with limited fecal data, used to estimate the quantities in the right-hand column of Table 20.2. The sloped line represents an exponential function fit to the ordinates 9,000 at about 1 d and 100 at 60 d, approximating daily urinary output just before the first DTPA treatment and well after the last, respectively. The average increase in excretion rate after a single DTPA infusion is seen to be about 5 to 7 times the base excretion rate without treatment. Data are reproduced from a copy of Fig. 3 in Wald et al. (1968).

measured by localized external counting for up to 1 y after the accident. Thus, the rapid translocation from the lung expected from these nitrate compounds of plutonium and americium did not materialize. Compounds that were classed as "soluble" in ICRP (1960) were assumed to have 0.25 of the intake taken up to blood from lung in about 1 d. Compounds that were soluble in water and deemed relatively soluble in lung fluids were found to complex in the lung, and the half-lives of plutonium in the lungs of dogs were found to be 500 d or more (Cember 1964; Stannard 1988).

This incident, as well as several others, showed that it was possible to use the Langham urinary and fecal excretion equations (Langham et al. 1950; Langham 1956, 1957) and the Beach and Dolphin (1964) empirical formulations of excretion vs. intake to obtain at least the correct order of magnitude of the early systemic burdens using the urinary and fecal data taken during the early months. The Beach and Dolphin (1964) and Healy (Healy 1967; Nelson 1972) formulations better approximated cases of less soluble material initially inhaled into lung that more slowly translocates to systemic circulation over time.

The simple Langham urinary function is

$$Y(t) = 0.2 \, t^{-0.74},$$

where Y(t) is the fraction of an initial bolus entering the blood on d 1 (by dissolution from the lung on d 1, or by injection) that appears in a 1-d urine on day t. Functions fitted to measured decreases in initial lung burden may be convoluted mathematically with Y(t) in order to relate urinary outputs with total translocations to the systemic circulation (as done by Healy [1967] for assumed exponential elimination from lung). This Langham function, combined with fecal and in vivo data, was most useful in assessing intakes from excretion in the early cases at the University of Pittsburgh. Moreover, this simple urinary excretion function is still within about a factor of two of those more recently used ICRP and other excretion models for up to about 10,000 d (ICRP 1979, 1980, 1993; Raabe 1994; Khokhryakov et al. 2002).

In Fig. 20.3, an exponential function has been fitted to the urinary excretion of plutonium over a 60-d period, generally using points before or well after DTPA treatments. (The absolute excretion quantities on this plot do not follow the simple Langham function, since there is no single systemic uptake but a long-term translocation from the lung. Also, the Langham equation gives the fraction [not the absolute quantity] of an initial uptake to systemic circulation that is found in the urine on day t. Use of the Langham function with these data indicated that, without DTPA, only about 1 to 2% of the lung burden of plutonium was transported to the system per day, even though the inhaled material was believed to be nitrate salts.) The approximately five times increase (average) after each DTPA treatment is evident; the DTPA effectiveness in removing plutonium and americium from blood (and to a large extent from soft tissues such as in liver) was determined later by a much larger series of measurements on another patient (Rosen et al. 1980). Thus, a "diagnostic" injection of DTPA was used to obtain an early indication of potential plutonium or americium systemic uptake. In the early days, rough initial estimates of plutonium uptake into blood were obtained under the assumption, recommended by Dr. W. D. Norwood of Hanford, that DTPA increased plutonium excretion by about a factor of 50 on the day following treatment. The increase in urinary excretion of americium was a much lower factor (about 5 to 7); americium was later found (by us and others) to be more transportable from lung to systemic circulation and into urine than some analagous oxides of plutonium, even without treatment.

This chapter uses documentation from some of the authors' own experience. There are now hundreds of papers in the literature with which future cases can be compared in order to obtain initial assessments of plutonium or americium intakes in individual cases where data become available (Raabe 1994; Bolch 2002; Kathren et al. 2003). Our own experience, as shown by medical examinations and radiochemical data, also indicated that even long-term, repeated, weekly injections with DTPA, especially when complexed with zinc, did not perceptibly harm the patient or his or her normal physiologic processes involving plutonium or americium (Slobodien et al. 1973; Rosen et al. 1980). The DTPA treatments were effective, as expected, in removing a portion of the body content of either americium or plutonium once the nuclides were in the systemic circulation or soft tissues. DTPA also helped translocate oxides of americium from the lung to some degree, much more so than for plutonium. The retention and translocation of plutonium and americium in soft tissue

and bone compartments is now represented by detailed, physiologically based mathematical models that take into account the findings of this case (Rosen et al. 1980) and much additional human and animal data (ICRP 1993).

Management lessons learned from this case, as well as the first, are included in the original paper (Wald et al. 1968); many of these same lessons are pertinent to the preparation of medical facilities expecting to evaluate and care for persons severely contaminated by a terrorist attack. There were long time periods between some of the urinary measurements, due to overloading of commercial laboratories that were not accustomed to analyzing many samples containing high amounts of plutonium and americium. This delayed decisions about DTPA effectiveness to some degree. In addition, the patient developed a paranoid outlook and for some periods did not trust anyone with his urine and did not supply samples. This represents a complication in managing radiation injury. The patient actually underwent an episode that required psychiatric treatment. A suspected contributor to this complication was the fact that a number of different physicians—the plant physician, hospital physicians examining the patient before he came to the university hospital, and others—might have presented different versions of his prognosis and consequent treatment.

Lessons Learned

The following lessons (summarized from Wald et al. 1968) are applicable to responding to attacks involving radioactively contaminated patients:

1. Analytical laboratories should be part of the medical-university or other center equipped to manage radioactively contaminated patients, or contractual arrangements and plans for performing all of the measurements and treatments necessary should be made between coordinated laboratories and hospitals in the same vicinity. Teams of physicians and health physicists must be organized, with assigned tasks and responsibilities, in advance of any need to receive contaminated patients. However, in any case, measurements of the 60-keV peak of americium with thin, shielded NaI detectors, together with estimates of plutonium/americium ratios taken from contamination or nose swabs of the patient, will probably be useful for triage, to distinguish those patients at significant risk from those who are not likely to sustain acute or long-term clinical effects.

2. Langham's equations can be used in the several months after exposure to aid in interpreting both americium and plutonium uptakes to the systemic circulation. After test or therapeutic doses of DTPA, the excretion rate in urine collected the next day can be expected to rise by a factor of up to 50 for plutonium and up to 7 or 8 for americium.

3. Even with this form of plutonium soluble in water, most of it remained complexed in the lung after initial treatments of DTPA, and a measurable amount was in the lung after 2 y. However, the treatments were apparently effective in reducing the total body burden of plutonium and americium substantially (see Table 20.2).

Inhalation of Metallic ^{192}Ir

Initial Scenario. Two employees of a local Pittsburgh area industry accidentally inhaled insoluble particles of ^{192}Ir on 14 January 1967 and were kept under periodic examination for 2 y in the University of Pittsburgh whole-body counter (Brodsky et al. 1967; Cool et al. 1979). An additional employee inhaled smaller quantities and was also followed over a limited time.

The inhalation incident occurred about 11:10 a.m., 14 January 1967, when a hot cell technician, seeking to open a capsule containing 2,000 Ci of ^{192}Ir pellets, accidentally cut into eight of the pellets. Just prior to introducing the iridium into the cell, the technician and his helper had adjusted the hot cell ventilation so that negative pressure was lost. They had inadvertently blocked off the main exhaust to increase the air flow through a local exhaust hood that increased air capture velocity at the cutting saw. About 75 Ci of ^{192}Ir were released from the source in the cutting process. Most of this material remained in the hot cell. However, as a result of the loss of negative pressure within the cell, about 2 Ci escaped through the slave arm and other penetrations. The general air samples in the hot cell operations area were stated to indicate an exposure of 125 MPC-hours equivalent, but subsequent whole-body counts indicated that much more radioactivity was inhaled by the two employees involved.

The iridium was apparently inhaled as submicron-sized particles of metal, with perhaps some oxide produced in the cutting process. A submicron aerosol was indicated because the exposure occurred on the operating side of the hot cell from material that was carried by entrainment in air streams that back-flowed from the hot cell through the openings in the hot-cell walls. Also, the aerosol was apparently diffused through the air breathed at the operating face and was invisible to the exposed workers. They went to lunch contaminated without knowing about their exposure. They returned to the plant about 2 h after the exposure and then checked their hands on a beta-gamma monitor. (An alarm was later placed in the operations area.) Thus, it is assumed that the two workers under examination were exposed to the same respirable aerosol for the same amount of time.

Patient Evaluation and Medical Management. The employees were decontaminated at the plant and were sent to the University of Pittsburgh whole-body counter about 8 h after the initial exposure. When they arrived at the facility, they were stopped outside the operations area, to avoid possible contamination of the *in vivo* counting facility, which was shielded and ventilated to maintain background levels about one-fiftieth of normal gamma background in the vicinity.

Measurements with portable scintillation-counter and GM-counter survey meters, at about arm's length, immediately indicated that one of the employees had an internal total body burden on the order of 1 to 2 mCi, and that his coworker had about one-third of this burden. (One mCi of ^{192}Ir was then considered to be the equivalent of an 8,000 MPC-hour exposure [ICRP 1960].) These quantities could not be accounted for by external contamination, even though external contamination was still too high to allow them to enter even our counter operations area containing the steel room and *in vivo* equipment. This case

again showed that decontamination at the plant could not be relied upon to accept patients for entry into a low-background counting facility. The workers were sent into the separate shower rooms to derobe and continue removing external contamination until very little more was removable. They then donned special robes and booties.

Immediate steps were undertaken at further decontamination and laxatives were given to accelerate passage of the contaminant through the GI tract and to reduce the GI tract dose. Calculations of possible GI tract and lung doses based on initial gamma intensities indicated that serious exposures might be incurred. All fecal and urinary excreta of the two higher-exposed individuals, except for spurious losses, were collected and the individuals were hospitalized for several days for further medical diagnosis and body burden evaluation. No chelation therapy was administered since none of the known therapeutic agents was expected to be effective against iridium metal, which is very insoluble in water and in all except the strongest acids. Thus, we waited to see whether ciliary and gastrointestinal clearance might remove enough material so that subsequent radiation exposures would not likely result in injury. External measurements with portable survey instruments already indicated at 10 h postexposure that a considerable fraction of the inhaled material had entered the stomach and low portions of the gastrointestinal tract.

Since such large burdens were present in these individuals, we decided to begin more precise body burden evaluations by having each individual stand outside the steel room on a marker at 8 feet from a 5-inch × 4-inch NaI crystal. There was no need for greater detection sensitivity with the quantities of activity in these two individuals, nor would it be appropriate to risk the removal of any additional contamination within the steel room. With this geometry, 1-min counts were taken for each patient facing the detector, with 1-min paired counts with each patient's back to the detector.

Since there were no immediate ^{192}Ir standards available, early burden estimates during the first day were made within a factor of three from known detector sensitivities and from the specific gamma-ray exposure rate of ^{192}Ir, as measured with calibrated survey meters. (A specific exposure rate of 100 mR-h^{-1} at 1 cm was calculated at that time to be associated with a point source smear of 19.6 μCi. Many more measurements of exposure rates from ^{192}Ir sources with different shapes and encapsulations have since been published in the medical physics literature. Probably the best current value for a bare point source is now a specific exposure-rate constant of 3.97 R-cm^2-mCi^{-1}-h^{-1} [Attix 1986], which translates to an exposure rate of 77.8 mR-h^{-1} at 1 cm for 19.6 μCi.) Relative measurements were controlled by counting at 8 feet a smear from the incident, sealed in a plastic bag, and corrected for the 74.2-d (Attix 1986) radiological half-life of ^{192}Ir. Initial corrections for body self-absorption were obtained by averaging measurements of the smear placed in front of, and behind, each patient, or a water phantom of appropriate thickness. These procedures show the necessity to improvise calibrations for unexpected geometries and radionuclide exposures to deal with very high initial burdens in serious exposure scenarios.

Later, when ^{192}Ir standards were obtained, more precise measurements were obtained with lung phantoms by matching spectra of lung phantoms and patients, using the several convenient gamma-ray lines of ^{192}Ir. Still, the feasibility of obtaining adequate assessment

for triage under emergency conditions, using simple calibration methods quickly adapted with contamination samples, was demonstrated with this exposure-assessment scenario. Even without a steel-shielded room, the gamma-ray intensity from these patients could have been initially assessed for a number of weeks with any degree of makeshift shielding. The decrease of lung burden in these cases followed closely the 74.2-d half-life of ^{192}Ir for many weeks (Cool et al. 1979).

After a period of several weeks and the assurance that no additional removable contamination would be shed within the steel room, the patients were counted both in a standard chair geometry within the steel room as well as at the 8-foot position. In this way, an accurate transfer of relative body content measurements was possible for increasing the accuracy of relative rates of clearance over a period of many months.

With the unusually high lung content of a gamma emitter in these patients, it was also possible to obtain lung scans with a Picker Magnascanner in the Nuclear Medicine Department of Presbyterian-University Hospital. The lung scans over several weeks showed a pattern typical of a uniform distribution of these submicron iridium particles throughout the lung alveoli for the several weeks over which the scans were taken. This information, together with material balances from fecal and *in vivo* measurements, showed that the lung retention of the two patients after 24 h was 6 and 13%, respectively, of the initially inhaled amount, the remainder exhaled or cleared through the fecal route with no urinary excretion.

These data were at the time compared to the ICRP (1960) model assumptions of 12.5% for the retention in the lung after 24 h of an inhaled quantity of 1 micron activity-median-aerodynamic-diameter (AMAD) "insoluble" particles. By the 1960 model, half of the quantity of an "insoluble" material initially deposited in the lung (25% of that inhaled) would be swept up in 1 d by mucociliary clearance and swallowed. These percentages from the 1960 model may also be compared with those of the 1966 ICRP model: 63% of the inhaled 1 micron AMAD particles are deposited, but 38% of the inhaled Class Y material, which is deposited in the nasopharyngeal (NP) and tracheobronchial (TB) regions, is swept into the GI tract in about the first day or two; also 0.4 of the 25% of inhaled material that is deposited in the (deep) pulmonary (P) region of the lung is removed to the GI tract with a 1-d half time. Therefore, at about 1 d, only 15% of the inhaled Class Y material will remain in the deep lung, compared to the 12.5% in the 1960 model (ICRP 1966, 1979, 1980, 1981 [see addendum for corrections]). The ICRP 1966 model was used in developing current regulatory standards in the United States (Brodsky 1996).

The more recent lung model (ICRP 1994) is too complex to assign general deposition fractions to large lung compartments, since it is designed to take into account many variables distributed in range such as particle size, breathing rates through nose and mouth of different breathers, and many other factors that might apply in particular situations, with the added provision of estimating uncertainty distributions in dose. However, a measurement within minutes or hours of the gamma radiation emanating from the body together with measurements of amounts in excreta within the first few days of exposure would also provide an early estimate of the amount inhaled. The inhaled amount, after following

individual translocation patterns for several days, might allow early estimates of the long-term internal doses and risks using current computer models incorporating the newer lung model, or using dose conversion factors provided in the appendices to this text.

If the measuring detector also views the nasopharygeal (NP) region, the remainder of interest from the 1966 model is 41% remaining of the total of 63% deposited in all of the NP, TB, and P regions of a quantity of 1 μm AMAD particles inhaled. It is apparent that the ICRP was cautious to not underestimate doses to lung from retained radionuclides that would remain in the pulmonary spaces for long periods of time. Of course, the default values of the 1966 model (or other models) might not apply to many individuals, so it is safer to collect all fecal material excreted over at least the first week after intake, and use the total fecal excretion to check model predictions using a material balance with measured quantities remaining in the lung. Also, consideration must be given to the possibility of contributions in these measurements from cleared material that might still be seen by the detector from positions in the alimentary tract. However, for all of these models, including the ICRP-66 model (ICRP 1994), it is seen that collecting total fecal excretion for the first few days, and multiplying the excreted activity by about a factor of two, will provide an early estimate of the order of magnitude of the inhaled quantity of Class Y material, which will allow an early assessment of lung dose together with confirmation of retention half-life by *in vivo* measurements.

It should be pointed out that there were no other adequate human data available to assist in the assessment of this case at that time. An earlier incident involving ^{192}Ir metal inhalation was not assessed for over 1 mo, so no activity measurements were obtained in that case. ICRP (1966) assumed that the half-life of iridium in the human would be 14 d based on the injection of soluble iridium compounds into rats. Later, the ICRP-30 reports (1980) misinterpreted and referenced our early report (Brodsky et al. 1967) to list ^{192}Ir compounds in Class W. Our long-term measurements, as indicated above, showed no biological removal of iridium from the lung after initial mucociliary clearance and no measurable ^{192}Ir in the urine, despite the large initial depositions in both cases. (Measurements of urine detected no ^{192}Ir and showed that there was less than 10^{-4} μCi excreted in urine per day, which was less than one-millionth of the remaining lung burden per day. Fecal measurements after 3 d and up to several weeks indicated fecal excretion of less than 10^{-3} μCi d^{-1}.) Statistical interpretation of the long-term data indicated that the biological half-life of metallic iridium in the lung, even as submicron particles, was at least as great as about 700 d, and possibly infinite (Cool et al. 1979).

The final estimates of weighted committed dose equivalent to the two individuals were 10 rem and 4 rem (Cool et al. 1979). Using the equilibrium dose constant for all beta and electron radiation of $\Delta = 0.454$ rad-g-μCi^{-1}-h^{-1} and the dose schema of the Medical Internal Radiation Dose (MIRD) Committee of the Society of Nuclear Medicine (Weber et al. 1989), the lung dose from electron radiation based on an estimated 1,000 μCi in lung from the survey meter measurements, the 74.2-d half-life, an absorbed fraction of 1 for betas and electrons, and 1,000 g of lung, would be:

Lung dose, beta = (1,000 × 1.44 × 74.2) × 0.454/1,000 = 48.5 rad,

which, for a tissue weighting factor of 0.12 (ICRP 1979, 1991), would be about 6 rem weighted committed dose equivalent (ICRP 1979, 1980, 1991). The gamma dose to the lung, using the MIRD formulation and $\Delta = 1.72$ for gamma and x rays (Weber et al. 1989), and a *specific* absorbed fraction of $\Phi = 5 \times 10^{-5}$ in the 0.2 to 0.5 MeV gamma energy region (Cember 1996):

Lung dose, gamma = (1,000 × 1.44 × 74.2) × 1.72 × 5 × 10^{-5} = 9.2 rad,

and 1.1 rem weighted committed dose equivalent. The total dose for an initial lung burden of 1 mCi, as estimated from survey meter measurements at arm's length, is according to MIRD schema calculations a weighted committed dose equivalent of about 7.1 rem, in the middle of the range estimated by Cool et al. (1979) for the two patients. A threshold dose of 2,000 rem to the lungs of dogs to produce lung cancer by plutonium dioxide was extrapolated by normalization of times to life spans to an average dose rate threshold for humans of 11 rad per year (220 rem per year) after inhalation in early life (Raabe and Parks 1993). By comparing this to a conclusion by Howe (1995) that the relative biological effectiveness of alpha radiation to x-radiation of the lung (in human patients) is closer to 4 than 20, this would make an estimated threshold dose rate for low LET radiation to be closer to 44 rem per year (Brodsky 1996). It also appears, from probability of causation (PC) tables, that these two workers' lung exposures, though easily detected even with survey meters, would not lead to high retrospective PCs of lung cancer during their lifetimes (Brodsky 1996, pp. 70–81).

Lessons Learned

1. An early estimate of the maximum lung dose or dose equivalent commitment (ICRP 1991) for triage can be obtained by survey meter measurements of inhaled gamma emitters, if obtained within hours after inhalation. (See appendix for list of gamma or x-ray exposure rates at 1 m [arm's length] from point sources for radionuclides more likely to be encountered in accidental releases or intentional radioactivity dispersing devices [RDDs]. Also, see appendix for lists of internal dose conversion factors per unit activity inhaled.) An approximate initial correction for absorption of gamma intensity within the chest area can be obtained by using measurements of a thin smear sample of the same contamination, placed in air and in front of, and at the back of, an uncontaminated individual of similar body characteristics to the person being evaluated. The average self-absorption of the lung and ribs for material spread throughout the lung can be approximately corrected for by plotting the count-rate of the detector (at some appropriate distance) for the source in front of, and behind, the chest on semilog graph paper and taking the attenuation at the mid-point of the body as the divisor for correcting readings for comparison with point-source-in-air calibrations. Longer-term follow-up with more sensitive

detectors in rather simple measurement geometries can provide more precise determinations of internal dose from radionuclide forms that are relatively insoluble in lung fluids.

2. Two individuals of the same sex and approximate age can differ by a factor of two or more in their initial lung deposition from exposure to a similar atmosphere containing widely dispersed submicron particles. Moreover, one individual had a higher lung clearance rate during the first 24 h and a higher elimination rate (in feces) than the other, but the long-term measurements reversed that picture (Cool et al. 1979).

3. Rates of lung clearance, and other parameters for standard man, used in ICRP reports are invaluable for calculating safe (conservative) limits of exposure. However, they are not necessarily applicable to the determinations of intake and internal dose for an individual in any particular exposure scenario. In vivo and excretion measurements on the individual must be made initially, and for at least several days, in order to obtain an approximate indication of internal dose commitments.

4. On the other hand, although long-term examination of individuals who inhale material extremely insoluble in lung fluid is still necessary to evaluate with greatest accuracy their long-term dose commitments, immediate triage from initial measurements is not likely to be effectively contradicted by the long-term evaluations. Experience shows that it is not generally probable that an individual in an exposure situation will have an intake that is just within the range of uncertainty of initial determinations and also likely to result in short-term or long-term health effects.

Glovebox Accident Involving Plutonium-Americium Contamination and Hand Amputation

Initial Scenario. This accident involved an individual with a limb cut off in a glovebox, with enough plutonium-americium contamination around the region of amputation to result in millions of rem to bone and other organs if an appreciable amount of the contamination were to enter the systemic circulation (Brodsky et al. 1972). A description of this accident, and its radioactivity evaluations and medical procedures, shows how such a situation can be managed in order to avoid serious internal exposure of the patient or of personnel involved in his decontamination and medical care.

On Thursday, 14 December 1967, an employee of a Pittsburgh area firm working in plutonium fuel fabrication reached for an item in his glovebox and his glove was caught by a milling machine that tore off his right hand (see Fig. 20.4). Soon after the accident, at 6 p.m., the Radiation Medicine Unit at Presbyterian-University Hospital received a call that an injured employee (we did not know of the amputation) was on his way to the hospital and was possibly contaminated with plutonium and americium.

At 7 p.m., an ambulance arrived with the patient, driver, and a health physics technician from the plant. The ambulance was directed to the morgue entrance; the morgue contained the only tables available for examination and collection of contaminated wash water, and it was distant from the necessarily contamination-protected, low-background, *in vivo* counting facility. The patient was surveyed for external contamination while in the ambulance. No widespread removable contamination was found, so the patient was brought in and placed on a decontamination table. We learned that the patient had lost his right hand at the wrist. The patient was relatively calm and cooperative, and requested a drink of water. Within minutes after the patient arrived, the medical director of Radiation Medicine arrived, and a surgeon was notified. By 7:15 p.m., the company president arrived and asked whether the hand had also been brought to the hospital. He was very disturbed when he learned that the hand had not arrived, since the surgeon had informed us that the earliest possible anastomosis (reattachment) of a severed limb improves chances for a successful graft. He expressed a continuing concern that the hand be found and brought to the hospital immediately. The assistants who came with the patient said that the hand had fallen into the contaminated glovebox, and they did not know whether it had been removed. At this time (7:30 p.m.) the plant health physics supervisor (Roger Caldwell, deceased, who later received the Elda E. Anderson Award) arrived with the contaminated hand wrapped in plastic in an ice bucket.

The hand was immediately counted with a NaI crystal while in the ice bucket. The patient was then dressed in a hospital gown and rolled on a stretcher to the whole-body counter on the floor above. For convenience to the patient, doors to the steel room were left open, and the patient's stump was counted near the doorway, with a 5-inch D × 4-inch NaI crystal, with a 2-inch D, 0.005-inch-thick Al window, pointed toward the patient. The x-ray and 60-keV gamma spectra immediately told us (by 8 p.m.) that there could be up to several thousand "maximum permissible body burdens (MPBB)" (ICRP 1960) of Pu-Am present, most on the hand and stump. An initial estimate from the company president that the plutonium in the glovebox contained 600 ppm of americium (an ^{241}Am/Pu ratio activity ratio of 0.032) then indicated that the Pu-Am mixture could be up to tens of thousands of times the maximum permissible bone burden (ICRP 1960). Such an amount, if entering bone, could result in bone dose commitments in the tens of millions of rem, according to the ICRP (1960).

In order to save time while the patient's arm stump was being counted, the hand was taken (8 p.m.) from the whole-body counter to decontaminate it, debride the tissues near the wrist, and prepare the hand for reattachment. Counting information was given to the physicians as it became available, so they could continuously weigh the benefits of reattaching the hand vs. the risks of an internal burden of Pu-Am. Chances for a successful graft were estimated by the surgeon as 5 to 10%, decreasing to zero for any delay beyond about 9 to 10 h. Time was of the essence.

Additional measurements on the stump and debridements indicated that 20% of the activity on the stump had been removed. The remaining contamination on the hand and stump was still more than 100 times the MPBB. Cleaning and debriding the hand had

lowered surface contamination to about 10 μCi based on the health physicist's preliminary estimate of an Am/Pu of 0.1 (later measurements of the activity ratio indicated by 3:30 a.m. that the remaining activity was 4 μCi). This remaining activity was still more than 100 MPBB, but the contamination was then believed to be relatively fixed on the skin surface. No early urinalyses were available, but gross counts of excreta and the nature of the incident indicated that the internal body burden was at this time insignificant compared to the activity fixed on skin surfaces.

At 12:40 a.m. on Friday, 15 December, the difficult decision was made by the patient and his family, as well as the involved physicians and health physicists, to reattach the hand—despite its excessive residual radioactivity. Considerations included the youth of the worker, his right-handedness, location of the radioactivity, the availability of DTPA chelation therapy, and the likelihood of the patient's availability of multiyear observation.

Most measurements had been performed concurrently with preparations for the reattachment. The emergency had required key members of the medical and health physics staff to be available and in constant control of procedures into the night after a full day's work. The surgeon worked through the night reattaching blood vessels and suturing together the hand and stump.

At 1:30 a.m., about 8 h after the accident, the hand was perfused with saline and DTPA solution. Also, 1 g of DTPA was administered intravenously to the patient to immediately chelate any plutonium or americium that might enter the system. Then the rejoining operation began. Surgeons were requested to retain for survey any instruments coming into contact with the contamination, and to discard any wastes that might be contaminated into a plastic bag. Health physicists observed the operation from the balcony. The main arteries and veins of the hand and arm were rejoined and blood flow was restored to the hand. The operation was completed about 5:30 a.m., and health physicists collected wastes and checked contamination in the operating room from 6:30 to 7:30 a.m. Plutonium-americium contaminated wastes were sent back to the company, and slightly contaminated surgical instruments were taken to the University Radiation Safety Office for successful decontamination. The operating room was approved for routine use within a few hours. None of the hospital or surgical staff was found to be contaminated. These details provide an idea of the amount of time and effort needed to manage one highly contaminated and injured patient.

On Saturday, 16 December, the patient was taken to the whole-body counter and the reattached hand and arm were counted again, as shown in Fig. 20.4. Spectra were corrected for body potassium background by taking measurements with the hand shielded from the detector. The total contamination had not been reduced appreciably at that point by the reattachment operation.

Unfortunately, circulation in the fingers of the reattached hand did not improve quickly enough for tissue survival, so the hand was reamputated at 3:00–3:15 p.m. on Monday, 18 December. The hand was infused with formaldehyde and recounted after amputation, showing about 4 μCi (about 100 MPBB) still on the surface. Spectral shapes of the x-ray and 60-keV region from various orientations indicated that the contamination was still on the skin surface. Since reamputation of the hand was done approximately an inch higher than the
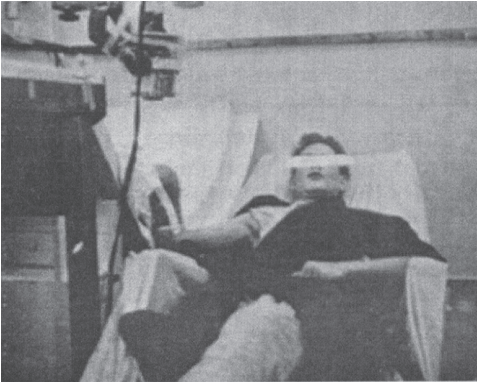
Fig. 20.4. Photograph of patient being counted for [241]Am contamination in a lawn chair with stump 17 cm below the window of a 5-inch D × 4-inch NaI(Tl) crystal, 19 December 1967. From Brodsky et al. (1972), with permission.

original accidental amputation, the reamputated hand turned out to contain practically all of the remaining contamination.

On Tuesday, the patient was brought to the whole-body counter and the activity on the stump was remeasured. The spectrum from the stump at 17 cm below the 5-inch D × 4-inch crystal showed only 0.008 μCi of [241]Am remaining on the stump. The spectrum of the 8-inch D × 4-inch crystal against the patient's back indicated that there was no appreciable lung or systemic burden (less than 0.002 μCi of [241]Am). After the first 2 d, there was no measurable plutonium-americium activity in the urine, so either no activity had entered the system, or whatever had entered during the reattachment operation had been chelated and removed by the DTPA. Further measurements of alpha surface contamination on the skin indicated that the small remaining skin contamination was removed when the last scab separated from the skin surface on 30 January 1968. Further whole-body counter measurements detected no remaining activity in or on the body.

Measurement spectra and other details of this case may be found in Brodsky et al. (1972).

Lessons Learned

1. An injured patient with enough external americium-plutonium contamination to provide a potential internal dose commitment of millions of rem can be properly managed in a hospital environment without expectation of serious internal exposure of the patient or staff, without appreciable remaining contamination of hospital facilities or equipment, and without causing undue fear or concern in the patient or staff. However, this appropriate management requires prior training and preparation by medical and health physics professionals familiar with the procedures described in this case summary.
2. An early estimate of the amount of skin contamination of a plutonium-americium mixture, on various areas of skin, can usually be obtained by placing a thin-window NaI crystal close to each area of interest and shielding the crystal from other

parts of the body with lead sheet. Skin contamination can be differentiated from internal systemic activity by examining ratios of x-ray to 60-keV intensities, measured on each side of a limb. In any case, the diffuse photon source from activity spread throughout the body will not likely interfere with any measurement of serious amounts of skin contamination. Absolute activity estimates can be obtained using a smear of the same contamination to which the patient was exposed, and the Am/Pu activity ratios as determined by alpha spectrometry of the activity on the smear.

3. Early estimates of any high activity deposited within the lungs can be obtained by decontaminating skin on opposite areas of the chest and back with Schubert's solution (see Table 20.1) and then counting activity in defined volumes of the chest region using NaI crystals collimated with lead sheeting. Although 60-keV photon measurements outside the chest are not much attenuated (beyond the spectral region of interest) by scatter within the body tissues (Bukovitz et al. 1969; Bukovitz and Brodsky 1970), the 60-keV photons are easily attenuated by thin sheets of lead. Early estimates of lung deposition can be confirmed by counting excreta cumulated for the first few days or 1 wk following the intake.

4. The medical management of an injured and contaminated patient in this case required at least about two person-days of professional dedication of a medical-health physics team already experienced with accidents involving external and internal contamination with americium-plutonium mixtures; this input was in addition to collaboration with a number of other physicians and medical and health physics technicians. The average medical institution likely to receive contaminated victims of a terrorist attack will not have such personnel or equipment resources. Any expectation of a medical capacity for triage and management of such patients requires prior training and equipping of personnel in each medical institution for the simplest counting and spectrometric measurements, and ready-made methods of data interpretation. Otherwise, as sad experience has shown, seriously injured but not radiologically dangerous patients will be refused needed care, and/or a large number of uninjured persons who are not at serious risk of radiation exposure will be sent to flood the more experienced institutions. Probably the best personnel to be prepared to receive contaminated patients in the average medical center are the nuclear medicine staffs of the more than 10,000 hospitals licensed to use radioactive pharmaceuticals in the United States.

Worker Exposed to Inhalation of ^{241}AmO$_2$ over a Two- to Three-Year Period

Initial Scenario. On 31 May 1967, a technician was brought to the University of Pittsburgh whole-body counter upon the recommendation of an Atomic Energy Commission (AEC) inspector, who had noted in company bioassay records that low-level alpha activity had been indicated in some of the technician's urinalyses. However, the urinalysis records

from nine sampling dates over a period from 21 August 1964 to 19 May 1967 were obtained from analytical procedures of questionable detection capability. Split samples analyzed at different laboratories on 14 March 1966 and 19 May 1967 were not in agreement.

Initial 40-min counts on 31 May 1967 with an 8-inch D × 4-inch NaI crystal against the back of the chest and a 5-inch D × 4-inch crystal about 1 m above a simulated standard chair geometry gave net counts above controls of about 1,059,000 counts in 40 min and 19,000 counts in 40 min, respectively, over the 60-keV americium photopeak region. These counts, compared against a source of americium in the lung region of a humanoid phantom, yielded initial body burden estimates of 1.04 and 0.96 μCi of ^{241}Am, respectively.

The work procedures and associated air monitoring data are described here for their value in illustrating the limited potential for intake of radioactive material, even for a worker continuously handling at arm's length up to 15,000,000 times the MPBB for americium in a dusty operation at one time. This information will help to place limits on the likely exposure of persons at other distances downwind from the release of large quantities of the most radiotoxic nuclides in any terrorist attack (Brodsky 1980, 1992).

The technician brought to the hospital was a glovebox operator who had prepared foils containing americium oxide powder by pressing about 200 mg mixed with several grams of gold powder into the bottom of a 0.5-inch × 1-inch die, and then pressing it into a 30-thousandths-inch-thick compact at a pressure of 30 tons per inch. The operator wore a half-mask respirator while transferring the powdered mixture through a pass box of the glovebox into the press hood where the compact was pressed. The operator worked in the press hood through an open door, keeping his mask on until the compact was pressed and the hood was cleaned up. A "small" amount of visible dust was sometimes released in the pressing operation in the hood. The final specific activity of the compact was about 3.17 mCi-mg^{-1}; each compact contained about 500 mCi of americium. The technician estimated that he made a total of about 50 of these compacts over a 2- to 3-y period and that his exposure probably was built up over this time, with a greater likelihood of exposure during the early part of this period.

The work in which the operator was involved also included removing the pellet from the box in which it was pressed to another box several feet away for sintering at 1,500°F for half an hour, followed by cooling in the oven overnight to room temperature. Then, the annealed compact was transported to a table where it was sandwiched between two 0.003-inch gold foils, heated in an open induction furnace (or the previous oven) to 900 to 1,000°F, and rolled. The heating and rolling were alternated by the operator until the compact reached the desired shape.

The operator wore no respirator after the initial sintering operation, and the rolling operation was performed without local exhaust ventilation. He also performed similar operations with about 100 mg of radium for each compact and for equivalent polonium activity, but for the radium and polonium there was a chemical reaction, as well as a physical mixing, between the radioactive material and the binder. On 25 May 1967, the operator was assigned to the health physics office at the plant and was removed from further possible

exposure to radioactive materials. In June 1967, the plant was shut down and process operations were redesigned. Americium was no longer handled in the plant after 1971.

A special breathing zone sample on 25 May 1967, the last day on which the operator was permitted to work with radioactive materials, showed a concentration of about 1.6×10^{-10} µCi-mL^{-1} during a 96-min operation during which three metallic foils were processed through the rolling operation, each foil containing only 82 mCi of ^{241}Am. (Note: If it is assumed that only this operation was conducted for each of 500 d, and that the employee breathed 10^7 cm^3 of air per workday, then the operator would have breathed 0.8 µCi in a 2-y period of work. Therefore, this air sample measurement, and the fact that most compacts contained more than 82 mCi, are compatible with the amount of americium activity remaining in the worker when he arrived at the hospital for evaluation.)

Patient Evaluation and Medical Management. After the initial assessment of a body burden of about 1 µCi at the University of Pittsburgh, the employer sent the patient to the Argonne National Laboratory (ANL), Radiological Physics Division for an assessment of the absolute quantity of americium in the body. ANL had a long history of research in *in vivo* counting and had developed a number of detector arrays to examine the distributions of radionuclides within the body (Toohey et al. 1983). Measurements at ANL indicated a total body burden of 1.8 µCi of ^{241}Am. With this "calibration" of total body burden, further measurements and long-term management of this patient were conducted closer to his home at the University of Pittsburgh. A grant was soon applied for and received from the U. S. Department of Health, Education and Welfare to assist in determining the most efficacious treatment regimen for removing this high amount of americium from this patient (Brodsky and Horm 1971). The body content was 1.8/0.05 = 36 times the then-recommended MPBB; an amount of 36 MPBB for this nuclide could not under federal regulations have been deposited in a worker unless the worker were exposed routinely to 36 times the maximum permissible concentration (MPC) in air for 50 y in the workplace. Such a deposition was projected to possibly deliver tens of thousands of rem to bone during the remaining lifetime of the patient (and somewhat smaller, but also high, doses to kidney and liver) (ICRP 1960). It was the highest body content of a nuclide of the plutonium-americium radiotoxicity family known at that time to have been deposited in a person in the United States.

After the ANL measurements, the patient was counted again at our university facility on 13 June 1967. In addition to total body measurements, counts were taken with collimated crystals looking at the patella and other bones of the leg. A collimated count over the patella drove the 60-keV peak off the scale of the multichannel analyzer display in 1 min, showing that much of the americium had already deposited in bone. The amount in bone was somewhat surprising, because colleagues at other laboratories and the literature (ICRP 1960) had indicated that ^{241}AmO$_2$ deposited in lung would be translocated to the system at an extremely low rate. The remeasurement of total body content on 13 June again indicated 1 µCi of ^{241}Am, using the same point source within the lung of a REMAB phantom as used for the first measurement on 31 May. Previous measurements with a point source moved to various positions in a cadaver had indicated that our calibration procedure would adequately

measure ^{241}Am distributed throughout the lung (Bukovitz et al. 1969; Bukovitz and Brodsky 1970). However, measurements showing that much of the americium had already translocated to bone, liver, and other soft tissue convinced us that the ANL determination of 1.8 μCi of ^{241}Am was the best estimate for the initial total body burden. Our own results indicated that our relative measurements were consistent and that the total body burden had not decreased between 31 May and 13 June. It became imperative for the medical director immediately to examine the potential effectiveness of chelation therapy and begin treatments.

Chelation Treatments and Evaluation. Sequential medical decisions regarding treatment regimens were determined not only by scientific principles, but also by the usual considerations involved in medical care with an agent administratively considered experimental, influenced by practicality from the standpoint of the employee, the changing policies of the Atomic Energy Commission and Food and Drug Administration, and other medical judgments that would not influence a purely scientific decision. Yet, the ensuing schedule of treatments appeared to be effective in removing more than twice as much body content as would have been removed by natural physiologic processes.

Between June and the beginning of chelation therapy in September 1967 with the calcium trisodium salt of diethylenetriamine pentaacetic acid (CaNa$_3$DTPA), baseline urine samples were evaluated by an independent contractor. When DTPA therapy began, enough radioactivity was in the urine so that samples could be measured by placing them on top of the 5-inch D × 4-inch NaI crystal (turned upside down) within the steel room. Self-absorption and volume differences were accounted for by using different volume water solutions of known amounts of ^{241}Am in containers of the same diameter. Fecal samples were obtained to determine total amounts of activity excreted by the fecal route as a function of time. Beginning in January 1969, bulk samples were measured at better geometry within a 900-cm^3 well within an 8-inch D × 8-inch NaI crystal, which had been purchased for these measurements. All samples were saved for the first few years in the refrigerated radiation safety office vault in the medical center.

The completeness of the daily samples brought by the patient on each visit, carefully packaged by his wife, was tested by plotting the cumulative distribution of daily excretions for two periods of time. The lognormal distributions for each period overlapped (Brodsky et al. 1971), indicating that the collection and packaging of samples at home was faithfully accomplished. Virtually all urine was collected from September 1967 through December 1974 while chelation therapy was being carried out (Rosen et al. 1980). Fecal collection was halted at wk 80. Excreta measurements with NaI crystals were soon accompanied by radiochemical separations, performed by a chemist obtained with funds from the government grant. Many of the chemical analyses of total ^{241}Am per sample, obtained by liquid ion exchange using HDEHP, were checked by measurements within the NaI well crystal before they were sent to the chemistry laboratory; radiochemical and NaI determinations were always in agreement. The radiochemical methods developed were also able to discriminate between the americium complexed and removed by DTPA and the americium complexed by natural physiologic processes and transported to urine (Horm 1971).

In vivo whole-body and organ counts were taken weekly between September 1967 and December 1968, until the schedule was changed and the patient began receiving chelation treatments closer to home.

The schedule of treatments and long-term results are given in detail in Rosen et al. (1980). Early collimated detector measurements indicated that most of the americium was already in bone, with appreciable amounts in liver, lung and other organs. This finding was confirmed by Harold May, of ANL, who indicated in a comment after our June 1969 presentation of results (included in Brodsky et al. [1971]) that his own measurements at ANL in June 1967 indicated that about 70% of the body burden was in bone at that time. A bone burden determination of 1 μCi of [241]Am in September 1967, before treatment began, was also consistent with the pretreatment urine data, if the urinary data were interpreted using Langham's equations (Langham 1956) relating urinary excretion to amounts taken into blood, and the assumption that americium is removed from bone at twice the rate for plutonium. In 1979, after cessation of treatments, the remaining body burden was 0.72 μCi of [241]Am, with most of the remaining burden in bone (Rosen et al. 1980). Additional determinations supported the conclusion that more than half of the removal of [241]Am from this patient could be attributed to the effectiveness of the chelation therapy.

During the 1 g per week treatment period from September 1967 to December 1968, the urinary excretion rate reached an equilibrium of 0.0055 μCi of [241]Am per week. Projecting by Langham's equation the 0.00154 μCi of [241]Am per week urinary excretion in the pretreatment period to the equilibrium measurement, assuming 2 y since the average intake, gave an expected excretion without treatment of 0.00114 μCi of [241]Am per week. The ratio of these values indicates an overall effectiveness factor of 5 in removing [241]Am for the continued 1 g DTPA per week over the first 65 wk of 1 g per week treatments, although Rosen et al. (1980) report a greater effectiveness factor of 10. The higher factor is apparently attributable to renewed increase in effectiveness after periods of cessation of treatment. The earlier effectiveness factor of 5 was also consistent with that determined by the HDEHP extractions of separate complexes of americium (Brodsky et al. 1971; Horm 1971). This effectiveness factor is the same as that later observed for the removal of zinc from the body during this period of chelation therapy (Slobodien et al. 1973). However, this zinc removal did not appear sufficient to affect the health of the patient, as determined from various laboratory tests (Rosen et al. 1980). Later medical practice used a DTPA compound incorporating zinc into the complex.

It is also of interest that the rate of elimination of americium activity, when converted to molar concentrations, was consistent with the rates of accretion and resorption of calcium in bone at equilibrium conditions of life. Apparently, the rate constant for resorption of americium atoms from bone surfaces might be about the same as for calcium. This finding was deemed to provide additional support to the belief that DTPA complexes americium or plutonium as soon as it leaves bone surfaces and transports the complex to urine for excretion (Brodsky 1971).

After removal of the patient from further exposure and mucociliary clearance from the upper respiratory tract for several days, fecal excretion rates were negligible until DTPA therapy began. Then, an initial sharp rise decreased to an excretion function with a 13-wk

half-life, interpreted as mainly due to removal of americium from liver by DTPA (Brodsky et al. 1971). Rosen et al. (1980) later estimated a 13.3-wk half-life during this period of fecal elimination. Integrating the fecal excretion during the first week of therapy with the remaining exponential elimination, Rosen et al. (1980) estimated that as much as 0.45 μCi of ^{241}Am was eliminated during the first 65-wk treatment period.

Measurements with a collimated detector showed that tissues of the testes or other organs in the gonadal area had concentrations of americium less than 0.001 of the concentrations in bone. Also, a 400-min count of a 3.4-g sample of semen on 24 October 1967, after DTPA therapy began, showed no significant activity, which was interpreted to show that the concentration of ^{241}Am in the patient's semen was less than 2×10^{-6} μCi of ^{241}Am per gram (Brodsky et al. 1971). According to ICRP (1993, p. 130), the percentage of americium leaving the circulation that deposits in male gonadal tissue (and is removed with a half-time of 10 y) is 0.001%. Thus, if 70% of the original burden of this patient (1.8 μCi), which is estimated to have translocated to bone when the patient was first examined, must have first passed into blood, the original deposition in gonadal tissue would have been $1.8 \times 0.7 \times 10^{-5}$ = about 1.3×10^{-5} μCi deposited in 16 g of testes, to give a concentration of $1.3 \times 10^{-5} / 16$ = about 8×10^{-5} μCi/g. This amount was below our detection limit, as indicated above.

Collimated measurements over other body areas during the first 2 y of chelation also revealed the more rapid removal of americium by DTPA from soft tissues than from bone (Brodsky et al. 1971). The ratios of counts over liver divided by counts over knee were about 9:1 in June 1967, 0.7:1 in October 1967, and 0.2:1 in November 1968. The ratios of counts over the right lung divided by counts over the knee were about 4 to 7 before DTPA treatment in September 1967, 1.6 on 16 October 1967, and 0.7 in April 1969. These ratios were only slightly lower 10 y later after a long period without treatment (Rosen et al. 1980).

Further details on the long-term evaluation of this case, including equations for some of the excretion and count data, are presented in Rosen et al. (1980). Some major findings are highlighted by the following tables and figures, which may provide concise guidance for the emergency management of future cases of intake of americium. Fig. 20.5 shows the fecal and urine elimination patterns during the first period of DTPA therapy; an approximate 15-wk half-life of exponential elimination in feces, probably most from liver, is evident on this semilog plot. Fig. 20.6 shows the overall decrease in total body activity, tending toward exponential elimination with a 24-y half-life as most of the removable americium has been depleted from the soft tissue compartments. In Fig. 20.7, the long-term decreases (over more than 10 y) in activity in knees, head, and chest show that the natural processes of elimination still tend to remove americium from the head and chest at a slightly faster rate than from the knees (bone); it should be noted that the chest data have been divided by a factor of two on this plot for close comparison with the other data. Although the rate factors apparently differ somewhat for the different tissues (note the tendency for the three upper curves to diverge, which they would not do on a logarithmic vertical scale if the ratios of counts remained exactly the same), the total body decrease still appears to be
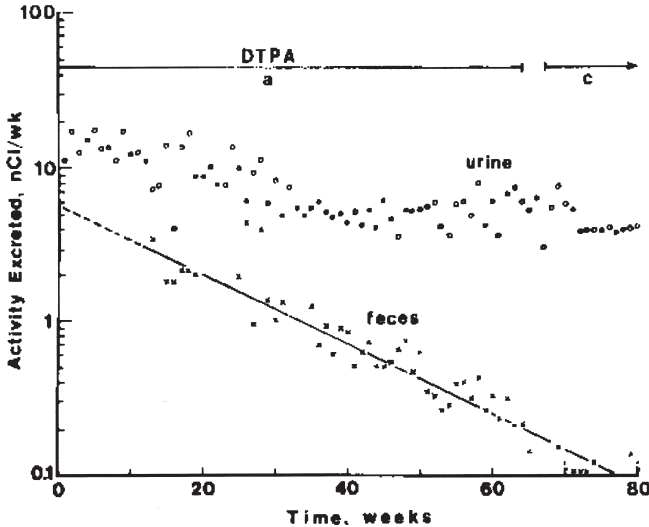
Fig. 20.5. Urinary and fecal [241]Am activity excreted during the first 80 wk of chelation therapy. The "a" period represents 65 wk of treatment with 1 g of DTPA per week, the "b" period is a 2-wk break, and the "c" period represents 14 wk with two 0.5-g treatments per week. The fitted function for fecal excretion was derived from data collected from wk 13 through 80 and appears to be consistent with the interpreted 15-wk half-life of removal to feces from liver in the earlier measurements (Brodsky et al. 1971). Adapted from Rosen et al. (1980), with permission.
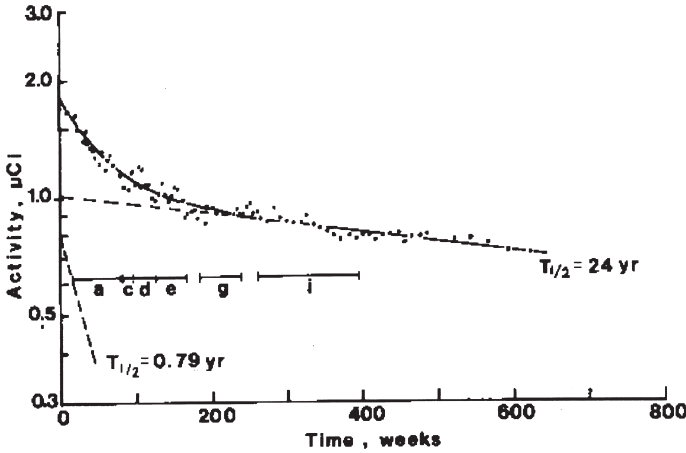

Fig. 20.6. Total body burden of [241]Am as determined by *in vivo* measurements, fitted by a two-component model to all data including those from nontreatment periods. Treatment periods are shown by the line segments a…i. From Rosen et al. (1980), with permission.

exponential, as seen in the lower total body data. Table 20.3 provides estimates of the half-lives for the several compartments illustrated in Fig. 20.7. Table 20.4 shows the relatively high remaining activity in the chest area (probably most in lung with some contribution from ribs), compared to the abdominal region; this indicates that there is a long-term component for removal of the material deposited in lung. This could be due to the fact that some of the dusts inhaled by the operator were the more refractory oxides of americium that he handled after high-temperature sintering and high-pressure compacting. That may also be the reason that a maximum-likelihood fit of the early urinary data to a Healy-Langham model (Healy 1957), which assumes a single exponential removal of material from lung to blood with each increment delivered to blood excreted in urine according to Langham (1956), did not provide a very satisfactory fit (Fasiska et al. 1971).

Lessons Learned

1. A patient who has inhaled enough plutonium or americium to possibly result in projected internal organ doses of tens or hundreds of thousands of rem can be evaluated and treated, with complete patient and family cooperation, over many years, without undue fear on the part of the patient or the family. Appropriate explanations can even convince at least some family members to collect and package excreta daily for months or years. Such a cooperative situation can prevail, however, only if the patient is explained the facts of the case by communication with only one physician who is expert in decontamination or radionuclide removal therapy, or at least by no more than two persons, preferably a physician-health physics team of two persons who are in continuing communication with each other.

2. Such high internal doses delivered over time are not likely to affect the health of the person, at least for many years, so an "effective threshold" for any effects within the first 10 y is probable. Thus, there is no need to retain such a patient, if uninjured, in the average medical institution responding to an attack or incident requiring the care of many individuals. There is time to send the patient to an institution with specialists to provide long-term treatment, or to prepare a local institution to manage the patient after the initial early response period.

3. DTPA therapy at 1 g per week in a single treatment is as efficacious as two 0.5-g treatments several days apart per week. A single 0.5 g per week treatment is somewhat less effective in removing americium already in blood or soft tissues. Americium already deposited in bone is not likely to be detached from bone by DTPA, but that removed by natural bone resorption is apparently largely complexed with the DTPA in the circulation and removed to kidneys and urine. These results are inferred from the liquid ion exchange results as well as from the counting data on body locations and urine and fecal samples.

4. Long-term (years) treatments with 1 g per week DTPA apparently had no ill effect on the patient over a period of many years of observation.

Table 20.3. Long-term clearance estimates of [241]Am for several body sites as derived from *in vivo* measurements.[a]

Site	Effective half-life (y)
Head	20 ± 3.6^{b}
Knees	42 ± 13
Chest	13 ± 2.3
Total body	24 ± 6.9

[a]From Rosen et al. (1980), with permission.
[b]One standard error.

Conclusions

The above case descriptions have been given to illustrate the range of external and internal contamination situations that could occur from the release of large amounts of radioactive material, as well as the ways such cases can be managed to avoid undue fear of such contamination and optimize reduction of internal dose. The case studies described are a part of a much larger body of literature on cases managed at other institutions. The results of these cases have now been utilized in the development of detailed mathematical models of the deposition, distribution, and excretion of various nuclides, inhaled under various conditions, for use in improved internal dose estimation for cases where long-term follow-up is available (ICRP 1979, 1980, 1991, 1993). However, the early models and data of ICRP (1960) can still suffice to provide early high-sided estimates of internal dose, for triage, using simple calculations tailored to emergency conditions.

Lessons learned can be seen in this paper to be supported by specific facts and measurements. They may be reduced to the following simple rules of thumb that can be conveyed quickly in an emergency, or explained in context with the facts presented in preparation for

Table 20.4. Count-rate distribution of [241]Am over the trunk of an oxide compact worker in 1976, about 9 y after last exposure and 100 wk after last chelation treatment, showing a continued major concentration in the upper chest regions. Measurements were made with a GeLi detector having an energy resolution of less than 20 keV full width at half-maximum. Values in the table are normalized to counts at the upper right chest.[a]

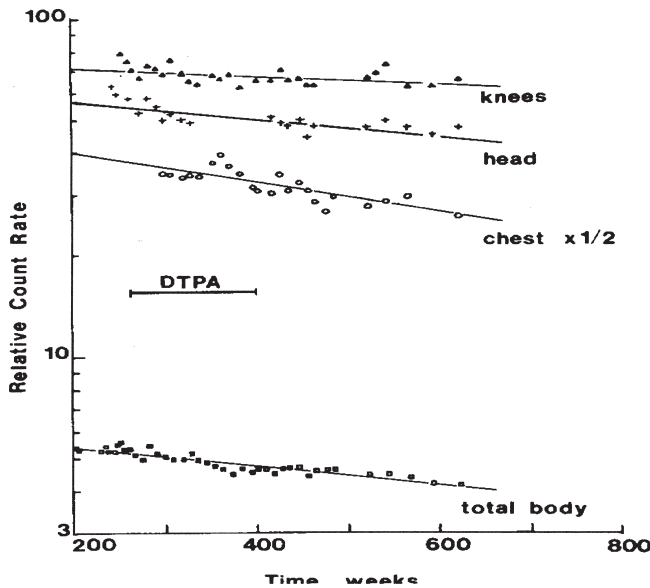| Site	Relative count rate	
	Right side	Left side
Upper chest	1.0	0.73
Upper abdomen	0.16	0.18
Lower abdomen	0.15	0.14

[a]From Rosen et al. (1980), with permission.

Fig. 20.7. Long-term clearance (time in weeks) of [241]Am from an individual body site as determined from *in vivo* measurements, both during and after DTPA treatments. From Rosen et al. (1980), with permission.

emergencies, to others responsible for care of radiologically contaminated and possibly injured persons.

General Rules of Thumb

1. Responders and the public should be informed that the release of radioactive material from a terrorist's radiological or nuclear bomb is not likely to cause serious harm at a distance removed from immediate blast effects, certainly if a person is indoors or not caught in a passing cloud of activity. Experience with release of highly toxic radioactive materials in the workplace (Brodsky 1980) has shown, in numerous cases, that even persons exposed to concentrations released at a distance of arm's length are not likely to have intakes that produce ill effects, either acute or long-term. Another chapter in this text also shows the usual limits on amounts of radioactivity that can be dispersed to populations from RDDs.

2. Early assessments of intake can be made for triage purposes with portable monitoring equipment, using the specific gamma or x-ray exposure constants for the single radionuclides of interest, as given in the appendices to this text and as illustrated in the above cases.

3. For a mixture of fission products from a short nuclear burst, or for fractions of specific radionuclides included in the release, estimates of potential internal dose may be obtained both from early measurements of exposure rates at 1 m from the chest, or from radioactive material collected on a folded handkerchief held over the mouth during passage of the radioactive cloud. A simple and rapid, but conservative, estimate of the seriousness of mixed fission product activity breathed into the lung, or collected on a handkerchief held while mouth-breathing in a passing cloud (which should pass within 1 to 2 min under most meteorological conditions), can be made by assuming that an intake of 300 µCi (about 600 million disintegrations per minute [dpm]) is equivalent to the risks of exposure to 25 rem of external radiation (Brodsky 2001). This rule of thumb is applicable, within a factor of two for periods up to about 30 d after release, to full fission product releases from either a bomb (short burst) or nuclear reactor fuel that has undergone fission for up to 3 y. Abundances of the radiobiologically important nuclides are given in Brodsky (2001) so that fractional releases of individual nuclides can be summed and taken into account. Assessments may be made from chest measurements by assuming one gamma photon per disintegration, of energy 0.6 MeV, for gross fission product mixtures. The rule of thumb can also be used at a reduced level of about 30 µCi (60,000,000 dpm) for a factor of safety to be well below 25-rem equivalent, and still be measured for triage with a portable survey meter measuring gamma or x radiation from the chest, or beta activity on a handkerchief or mask. Additional data are given in the appendices to assist in these triage determinations.

4. The levels of radioactivity or radiation that might be used as limits for triage of many persons in a population exposed to terrorist or accidental releases (which might in some cases not be distinguishable) are obviously many orders of magnitude greater than those maintained as precautionary limits under peacetime conditions. It is thus imperative that even experienced health physicists or physicians, knowing peacetime standards but never involved with higher level exposures, will need to be reoriented with the facts in the above cases and accident literature, in order to be able to focus on, and care properly for, persons who are injured and/or subjected to higher levels of radiation exposure and those associated with serious risk of harm. Such an orientation must also be passed on to responders and to the public in terms they can understand, with examples such as those provided in the cases above to ensure credibility.

5. If a patient is deemed in triage to require further decontamination and follow-up, further communication of the facts and ensuing events in the course of treatment should be provided by a single physician, perhaps working in continuing communication with a health physicist trained in emergency management of highly exposed patients.

6. Members of staff or others offering assistance, if not already given their tasks and training previously in an established plan, may best be dealt with by quickly providing *ad hoc* tasks and duties that might be constructive. Otherwise, it might

not be possible to avoid unnecessary interference with case management. In an emergency, every one (of those not afraid of the radiation) on hand wants to help. They must be given something to do, especially if there are no guards or security arrangements to ensure control. A single person must be in charge and prepared to issue immediate and helpful *ad hoc* orders to the participating staff members.

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