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# Doses to the Hand During the Administration of Radiolabeled Antibodies Containing Y-90, Tc-99m, I-131, and Lu-177

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# DISCLAIMER

# ABSTRACT

Exposure of the hands of medical personnel administering radiolabeled antibodies (RABs) was evaluated on the basis of (a) observing and photo-documenting administration techniques, and (b) experimental data on doses to thermoluminescent dosimeters (TLDs) on fingers of phantom hands holding syringes, and on syringes, with radionuclides in the syringes in each case. Actual exposure data for I-131 and Lu-177 were obtained in field studies. Variations in handling and administration techniques were identified. Dose rates measured using TLDs on the surface of loaded syringes were adjusted for differences in electronic stopping power, absorption coefficients, and attenuation between dosimeters and tissue to estimate dose-to-skin averaged over 1 $cm^2$ at 7 mg $cm^{-2}$ depth for Y-90, Tc-99m, I-131, and Lu-177. Dose rate coefficients to the skin, if in contact with the syringe wall, were 89, 1.9, 3.8, and 0.41 $\mu Sv\ s^{-1}$ per 37 MBq (1 mCi) for Y-90, Tc-99m, I-131, and Lu-177, respectively. For dose reduction, when using Y-90 the importance was clearly indicated of (a) avoiding direct contact with syringes containing RABs, if practical, and (b) using a beta-particle shield on the syringe. In using a syringe for injection, doses can best be approximated for the geometry studied by (a) wearing a finger dosimeter on the middle finger, toward the outside of the hand, on the hand operating the plunger, and (b) wearing finger dosimeters on the inner (palm) side of the finger on the hand that supports the syringe for energetic beta-particle emitters, such as Y-90 and Re-188.

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# EXECUTIVE SUMMARY

The objectives of this work were the following:

(1) review procedures employed in the administration of radiolabeled antibodies (RABs),

(2) determine, experimentally, the dose rates that potentially may be received if fingers or hands come in contact with syringes containing RABs used in typical procedures, and

(3) determine the shielding value of using thin plastic sleeves over the syringes.

During this study, the procedures used in the administration of RABs were observed at three medical institutions. These observations revealed that procedures vary from institution to institution. If syringes are held by hand, the skin of fingers could come in direct contact with the syringe's walls. This approach can give the skin much higher dose rates than recorded by the usually employed finger dosimeters. To estimate dose rates to skin in contact with syringe walls, and to determine the correction factors that would be needed to obtain dose estimates from finger dosimeters, a series of dose-rate measurements were made using finger dosimeters on phantoms of a hand, which held a syringe containing the isotopes of interest. In separate measurements, TLD dosimeters were also placed on the surface of the syringes for known periods to obtain related dose rates per unit of activity for comparison. Finally, calculations were made of relative dose to the skin of a hand or finger at 7 mg $cm^{-2}$ depth in skin, compared to average dose deposited in the TLD dosimeters. These ratios were then used to adjust the TLD readings to reflect dose to skin.

The results of TLD studies on the surfaces of syringes are summarized in the following table which indicates dose rates per unit activity and time to receive 0.5 Sv dose to skin in contact with a syringe containing 3.7 x $10^9$ Bq (100 mCi) of each isotope studied. The results show that, for syringes containing 3.7 x $10^9$ Bq (100 mCi) of Y-90, the 0.5 Sv skin limit can be exceeded in approximately 0.3 to 1 minute for contact with 3-cc to 12-cc syringes, respectively. For Lu-177, the limit is reached in 90 to 205 minutes, respectively. For Tc-99m and I-131, the times to reach the limit are intermediate between those for Y-90 and Lu-177. The dose rates measured on the surface of syringes in this work are useful as a reference because they are the maximum dose rates possible. However, the relationship between dose to a ring badge and dose rate on the surface of a syringe is likely to be very dependent on geometry.

Throughout this report, volume is expressed in units of ml, and the size of syringes is expressed in terms of maximum capacity (cc) to avoid confusion between the size of syringe and volume of its contents.

The larger syringes permit longer exposures due to greater self-absorption in the solution and a greater distance from the effective center of the source. The effectiveness of shielding on 12-cc syringes also was explored using cylindrical polypropylene shields. The reductions of dose rates on the surfaces of 12-cc syringes were exponential with half-value thicknesses equal to approximately 0.8 mm for Y-90, 1.8 mm for Tc-99m, 3.6 mm for I-131, and 4 mm for Lu-177. These results demonstrate the importance of using a protective sleeve over the syringe, especially for pure beta-particle emitting isotopes such as Y-90.

Finger dosimeters on the hand holding the syringe were shown to underestimate the surface dose-rate to skin by factors of about 50 to 2,400 depending on the isotope, finger on which dosimeter is worn, size of syringe,

and whether the dosimeter is worn on the palm-side or outside of the finger. To avoid unnecessary finger exposures, the use of shielded syringes is preferred.

**Summary of estimated doses to tissue averaged over 1 $cm^2$ at 7 mg $cm^{-2}$ depth, and half-value thicknesses for polypropylene shields.**

| Radio-nuclide | Syringe Size, cc | Solution Volume, ml | Half-value Thickness, mm | Corrected tissue dose-rate coefficient, mGy $s^{-1}$ $TBq^{-1}$ | Corrected tissue dose-rate coefficient, mrad $s^{-1}$ $mCi^{-1}$ | Time to receive 0.5 Sv to skin for 3.7 x $10^9$ Bq (100 mCi), min |
|---|---|---|---|---|---|---|
| Y-90 | 3 | 2.2 | | 8295 | 31 | 0.27 |
| | 6 | 4.6 | | 5439 | 20 | 0.41 |
| | 12 | 8.6 | 0.8 | 2415 | 8.9 | 0.93 |
| Tc-99m | 3 | 2.0 | | 72 | 0.27 | 31 |
| | 6 | 4.0 | | 58 | 0.21 | 39 |
| | 12 | 8.0 | 1.8 | 52 | 0.19 | 43 |
| I-131 | 3 | 2.0 | | 224 | 0.83 | 10 |
| | 6 | 4.0 | | 163 | 0.60 | 14 |
| | 12 | 8.0 | 3.6 | 103 | 0.38 | 22 |
| Lu-177 | 3 | 2.0 | | 25 | 0.092 | 90 |
| | 6 | 4.0 | | 17 | 0.063 | 132 |
| | 12 | 8.0 | 4.0 | 11 | 0.041 | 205 |

# FOREWORD

The Nuclear Regulatory Commission (NRC) became aware some years ago that radiolabeled antibodies (RABS) were being developed for medical applications including cancer diagnosis and treatment. In order to develop a technical base to support licensing and regulatory decisions and to understand better the potential hazards associated with new biochemistry, larger quantities of radioactivity and the new uses of alpha and beta emitters, the NRC contracted with BNL to develop a series of technical reports.

Three reports already published are NUREG/CR-4444, "Radiation Safety Issues Related to Radiolabeled Antibodies," NUREG/CR-5877, "Aspects of Monitoring and Quality Assurance for Radiolabeled Antibodies" and NUREG/CR-6374, "Wholebody Effective Half-Lives for Radiolabeled Antibodies and Related Issues."

This report looks at typical procedures used by technicians and physicians in administering selected RABS and associated hand doses that result. The report makes recommendations for measures such as syringe shields that might be used to control extremity doses expected from the higher activities and the use of beta emitters.

The results, approaches, and methods described in this NUREG/CR-6493 are provided for information only. Publication of this report does not necessarily constitute NRC approval of, or agreement with, the information contained herein.

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# 1 INTRODUCTION

The general problem of radiation safety issues associated with the use of radiolabeled antibodies was addressed in NUREG/CR-4444, BNL-NUREG-52275, "Radiation Safety Issues Related to Radiolabeled Antibodies" (Barber et al., 1991). The specific question of effective half-lives of administered RABs was considered in "Whole-Body Effective Half-Lives for Radiolabeled Antibodies" (Kaurin et al., 1996).

Related to these reports, Brookhaven National Laboratory (BNL) was asked by the Nuclear Regulatory Commission (NRC) to investigate, in greater detail, the potential and actual doses to the hands of medical personnel administering antibodies (RABs). The objectives of this work were the following:

(1) review procedures employed in the administration of RABs,

(2) determine, experimentally, the dose rates that may potentially be received if fingers or hands come in contact with syringes containing RABs used in typical procedures, and

(3) determine the shielding value of using thin plastic sleeves over the syringes.

Some procedures with radiolabeled antibodies involve activity levels and volumes of solutions larger than those used in more common pharmaceutical procedures (Barber et al., 1991). Hence, an examination of the dose rates to the fingers of those who handle RABs is appropriate. There also is need for additional technical data to provide the basis for optimal control of worker exposures.

Kereiakes and Corey (1976) demonstrated the importance of dose distribution and geometry to the dose to the skin of a hand holding an unshielded syringe in one particular injection geometry using a rubber glove filled with paper mache, beryllium oxide thermoluminescent dosimeters (TLDs), and a partially filled syringe containing 740 MBq (20 mCi) of Tc-99m in 2 ml. The authors did not specify the size nor composition of the syringe used. However, dose rates at the surface of the syringe were shown to vary by orders of magnitude depending on the location with respect to the active volume.

Husak (1971) proposed a formula to approximate the maximum exposure rate from gamma radiation at the surface of a cylindrical volume of radioactive liquid. For Tc-99m, he predicted a maximum exposure rate of 0.0014 C $kg^{-1}$ $h^{-1}$ (5.5 R $h^{-1}$) from 740 MBq (20 mCi) in a 10-cc glass syringe. This exposure rate is 26% of the maximum exposure rate reported by Kereiakes and Corey (1976). Better estimates of dose rates are important for controlling the dose.

The surface dose-rates from radiopharmaceuticals can be very high (especially for beta-emitters such as Y-90), depending mainly on the attenuation provided by a container. Measurements of dose rates from syringes of various sizes were required to determine maximum dose rates to the skin of the hand, and to determine the best location for finger dosimeters to be worn to yield a result representative of the dose. Information was gathered for the former section by a combination of correspondence, in-depth telephone conversations with, and visits to, selected institutions. Telephone inquires were first made of eleven institutions actively involved in RAB therapy. Four of these were selected for visits, and three for photo-documentation of activities (the fourth was doing only diagnostic procedures at the time of the visit). At three of the four institutions visited, therapy infusions, or mockup demonstrations were observed and photo-documented. Information also was gathered during these visits on hand and whole-body doses of medical personnel administering RABs. Section 2 describes the methods of RAB

infusions at these three leading institutions as they pertain to exposure of the hands.

Section 3 compares the results for doses at 7 mg $cm^{-2}$ skin depth averaged over 1 $cm^2$ (the standard now used for regulating skin dose) to measurements of dose to 3.2 x 3.2 x 0.89 mm thick TLD detectors taped to syringes, and measurements of dose to phantom hands in one particular geometry. Adjustments to the TLD measurements were needed to account for differences in dose to the LiF compared to tissue, and for variations in dose with depth in the TLD which was thick (0.89 mm) compared to 7 mg $cm^{-2}$ of tissue.

Since some procedures with RABs involve activity levels and solution volumes larger than those used in other common procedures (Barber et al., 1991), experimental studies were made of doses to the fingers and hands of those who handle RABs in syringes. For these studies, Y-90, Tc-99m, I-131, and Lu-177 radionuclides were employed in 3-cc to 12-cc polypropylene syringes. The skin doses to the fingers were measured using small TLDs on phantom hands using one particular geometry. Measurements were supplemented with calculations to estimate doses averaged over 1 $cm^2$ at a depth of 7 mg $cm^{-2}$ in tissue. The results from these studies are summarized in Section 4. Sections 5 and 6, respectively, contain the discussion and our conclusions.

The exposures received by radiopharmacists (although generally the highest reported hand dose at each institution) were not considered in this report because their exposures are due primarily to non-monoclonal antibody exposure.

Throughout this report, volume is expressed in units of ml, and the size of syringes is expressed in terms of maximum capacity (cc) to avoid confusion between the size of syringe and volume of its contents.

For the initial experimental determinations, we contracted to determine dose rates from Sr-Y-90, Tc-99m, I-131, and Lu-177, however, during subsequent visits to institutions using RABs, we additionally obtained data on the use of Re-188. These data are presented for completeness.

# 2 EVALUATION OF EXPOSURES OF THE HANDS ON THE BASIS OF OBSERVATION, CALCULATION, AND DOSIMETER READINGS

## 2.1 Abbreviated Description of Technique for Radiolabeled Infusions at Institution #1

The observations focused on use of Lu-177 and I-131 labeled monoclonal antibodies, the most often used at this institution. The RAB is prepared to be administered by gravity fed drip technique. The same basic technique is used for intravenous and intraperitoneal infusions.

### 2.1.1 Preparation and Infusion of RAB

The solutions are prepared by the radiopharmacist or the assistant, a nuclear medical technician. Lu-177, which emits 0.5 MeV (maximum energy) beta particles with 11% of the betas having an associated 206 kV gamma ray (Table 3.1), is manipulated behind 2.5 cm-(1 inch) thick Lucite shields. The radionuclide, received from an outside supplier, is injected into a 50-cc standard serum-albumin vial. The vial then is placed within a small cylindrical-like shield which is rigged for hanging in an inverted position so that the mouth of the vial is accessible through a hole in the bottom of the shield. The entire apparatus is placed in a large lead container mounted on wheels for delivery to the patient's room.

I-131 is prepared and the samples are processed remotely in a lead-shielded hood using mirrors, with the tubing from the process column passing in front of a Geiger-Mueller (GM) tube, so that radioactivity can be monitored during the process. Solutions are checked using a CAPINTEC®[1] calibrator. Three to five seconds are required to remove the sample from the shielded container and place it in the calibrator, or to remove it from the calibrator and place it back in the shielded container. No further manipulation by physicians, nurses, or technicians is required. Each experimental protocol has a different nurse assigned, so that it is not necessary to train more than one individual for each protocol.

The infusion procedure is described briefly as follows. The lead shield containing the RAB is hung from an apparatus attached to a ceiling hook (Figure 2.1). The tubing from the shielded vial is connected to the patient and tested for patency. The flow rate is adjusted to deliver the total volume in approximately one to two minutes. Following the infusion of the labeled material, the apparatus is flushed directly by syringe, and an additional 100-cc of nonradioactive solution is infused through the tubing from the drip bag of solution. This ensures that the patient receives most of the radioactivity and allows better distribution of the antibody within the peritoneal cavity. The upper part of the tubing is flushed by injecting 20-cc of media directly into a Y connector at the base of the vial, whereas the additional 100-cc of nonradioactive solution is infused lower in the tubing. The hand and syringe geometry shown in Figure 2.1 is similar to that employed in phantom studies described in Section 3.

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[1] Capintec Radionuclide Calibrator Model CRC-7, Capintec Manufacturing, Ramsey, NJ 07446.

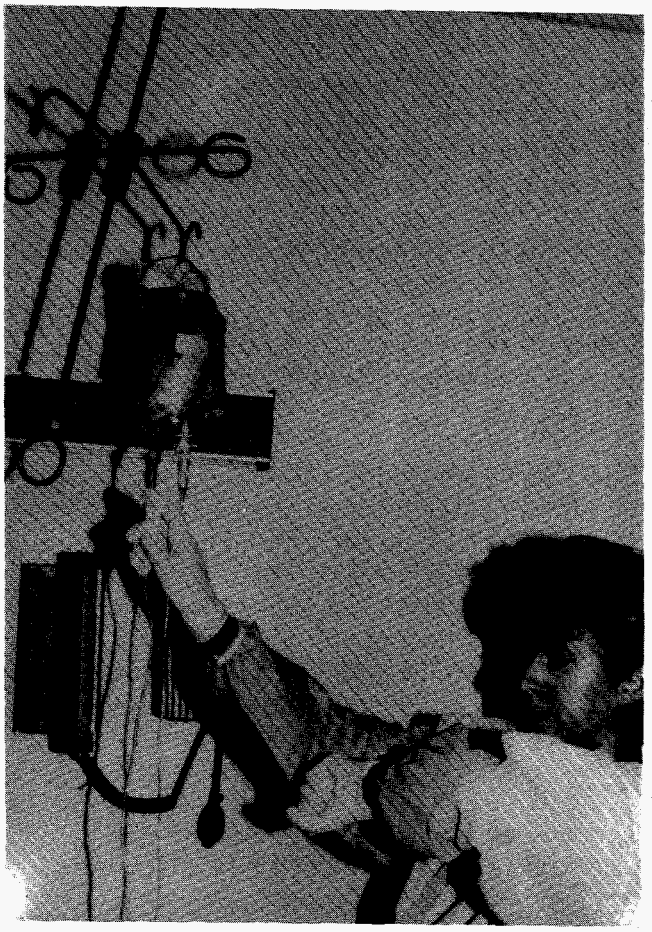

**Figure 2.1** One method of RAB infusion used at Institution #1. The RAB solution is injected into the serum bag from which it is infused into the patient. The technician is adjusting the flow of the solution to the patient.

### 2.1.2 Measurements of Dose Rates

The dose to the nurse's hands would arise primarily from three activities:

(1) Connecting the tubing to the vial and setting the drip rate takes approximately 20 to 25 seconds, during which time both of the nurse's hands are in contact with the tubing for approximately 5 to 10 seconds, and one hand is in contact with the tubing for the full 20 to 25 seconds.

(2) Flushing the tubing is the second source of exposure. This operation, of approximately 30 seconds, takes place with an exposure geometry that yields a dose rate of approximately 550 μGy/h (55 mrad/h).

(3) Disconnecting the tubing apparatus and placing the empty tubing and vial into the large lead shield requires approximately 20 to 25 seconds. During this time, the survey meter indicates approximately 50 μGy/h (5 mrad/h) with the meter at contact with the tubing (hereinafter referred to as "at contact").

Survey measurements were made with a Ludlum®[2] Model 13 survey instrument with a thin window probe.

Before beginning the infusion, the lead shield containing the RAB reads 50 μGy/h (5 mrad/h) at contact. Once the tubing was fitted and full, the exposure from the entire length of the tubing read approximately 500 μGy/h (50 mrad/h) at contact. Immediately before flushing, the radiation level was 550 μGy/h (55 mrad/h) at one inch from where the infusion tube exits below the container. This value is a combination of approximately 500 μGy/h (50 mrad/h) from the tubing and an additional small amount (approximately 50 μGy/h (5 mrad/h)) from the residual activity in the container. The reading at one meter from the tubing was 38 μGy/h (3.8 mrad /h) and, at two meters approximately 15 μGy/h (1.5 mrad/h). After flushing, the area that read 550 μGy/h (55 mrad/h) then read 50 μGy/h (5 mrad/h).

Table 2.1 summarizes the radiation level measurements, hand exposure times, and

[2] Ludlum Measurements Inc., P.O. Box 810, Sweetwater, TX 79556.

calculated hand doses.

All personnel associated with RAB infusions wore ring-type finger dosimeters on at least their dominant hand. The dosimeters are changed monthly and exposures reported quarterly. Table 2.1 shows the dose values considered to be most representative for exposures due to infusion activities similar to those observed and used for calculating hand exposures. It must be noted that ring dosimeters reflect all exposures for the entire dosimetry period, and not just for the infusion procedures.

Separate dosimeters worn only during infusions would give more accurate estimates of infusion-related doses; however, this is not being done nor contemplated at present, since this information is not of prime interest to the involved individuals.

## 2.2 Abbreviated Description of Technique for the Infusion of Radiolabeled Antibodies at Institution #2

At this institution, the RAB is prepared for intravenous gravity drip administration. The observations focused on the use of I-131, although some information also was gathered for Re-188 labeled antibodies. The significant differences in radiations emitted from these two radionuclides (Re-188 being primarily a beta-particle emitter, and I-131 being both a beta-particle and a gamma-ray emitter) present extremes in shielding needs, handling techniques, and choice of release criteria.

### 2.2.1 Preparation and Infusion of RAB

The antibodies are labeled in a shielded hood in the radiopharmacy of the outpatient clinic. All shields (e.g., for hood, reservoirs, syringes) are designed to accommodate the use of I-131, and, thus, are more than adequate for Re-188. The radiopharmacist withdraws the proper amount of RAB from the shipping container using a shielded syringe.

The activity of the material is determined using a Syncor®[3] radioactivity calibrator. The results of the measurement, together with all of the pertinent data, are recorded on a standard form, which is kept with the radionuclide-containing syringe and checked by the physician or technician before infusion. For use in the outpatient clinic, the loaded syringe is carried in a shielded container to the infusion area in the same building.

For use outside the clinic, the radionuclide is placed in a 250-cc serum vial and transported to the place of use in a larger shielded container.

Two different techniques are used for infusion. The desired amount of antibody is delivered to the patient's room in a shielded 250-cc vial with a rubber membrane seal. During infusion, the vial is held in a small lead cylindrical shield that has a small opening at the bottom allowing the neck of the vial to protrude for access. The top end of the shield is open to allow the vial to be inserted into it; the vial is inserted neck down in preparation for infusion. The bottom of the vial extends above the top of the small shield when it is sitting on the table because the neck of the vial is pushed back into the opening of the shield on the bottom. Two technicians place the vial in the small shield in the hanging position with the cover in place. At this time, the solution is in the shield and the exposure is negligible. From this point on, only one technician is involved, therefore, the exposures discussed relate to this technician. For infusion, a tubing with a sharp catheter tip is inserted through the

[3] Syncor Model CRC-12, Capintec Manufacturing, Ramsey, NJ 07446.

rubber membrane at the neck of the vial which, in turn, is connected to a flow control device to the patient.

Inpatients usually receive I-131 doses ranging from 0.56 to 9.3 TBq (15 to 250 mCi) with an average of 5.6 to 5.9 TBq (150 to 160 mCi). This activity is contained in 90- to 150-cc of solution. No documentation is available on exposure or administration techniques for inpatient treatments because these take place in several outlying hospitals using the radionuclides prepared and shipped from this institution.

The second infusion technique, which is used at the outpatient clinic, involves a lead-shielded burette (Buretrol®[4]) reservoir. These infusions are routinely carried out by a physician or nuclear medicine technician. The 10-cc syringe employed usually contains approximately 9-cc of injection solution. A drip bag containing non-radioactive flushing solution is hung from the same support as the Buretrol and connected into it for flushing. After injecting the radionuclide into the Buretrol, the syringe is rinsed twice with non-radioactive solution drawn from the drip bag, and each time the rinse is injected into the Buretrol.

After the injected solution and the two syringe flushes are infused from the Buretrol, an additional flushing solution is flushed directly into the Buretrol from the drip bag. The total amount of infused material is approximately 50 cc.

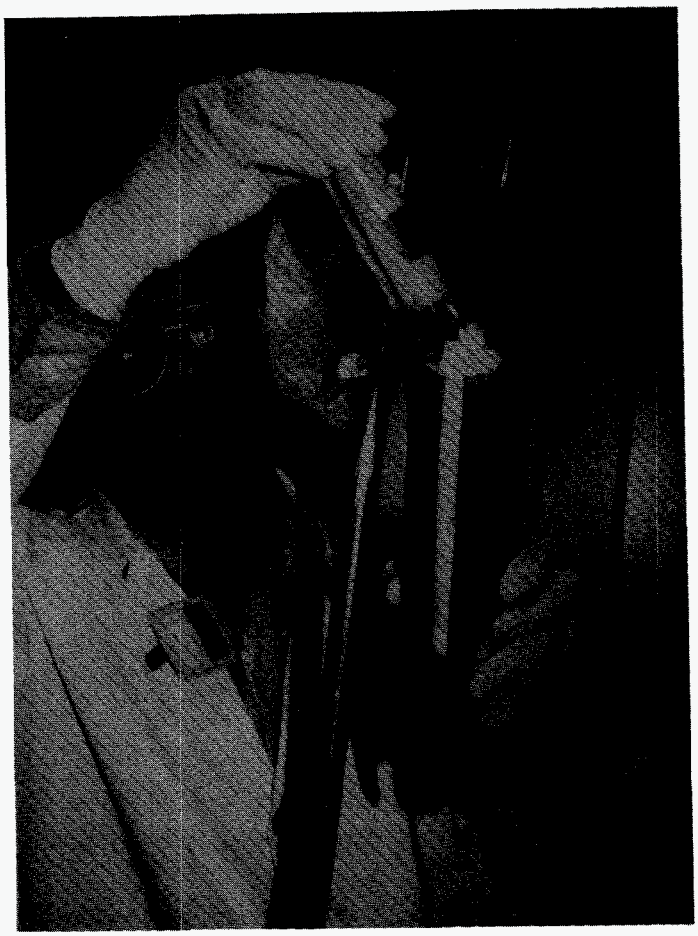

**Figure 2.2** One method of RAB infusion used at Institution #2. The RAB in a shielded syringe is shown being injected into a shielded container from which it is infused into the patient.

### 2.2.2 Measurements of Dose Rates

The dose to the nuclear medicine technician or the physician would arise from two activities:

(1) Injecting the radionuclide into the Buretrol for treating the patient (here, the amounts were documented).

(2) Disconnecting the infusion apparatus for the high-level treatments, which might

[4] Buretrol, Baxter Health Care Company, Dearfield, IL.

present a moderate hazard. However, readings were not available for these dose levels, since these treatments were not being carried out at the time of this study. The RABs for inpatient use at other hospitals in the area are shipped in the same small shield that is used for holding them during infusion at this institution. Therefore, it is reasonable to expect that exposures would be similar at all hospitals using this method.

The data discussed for Institution #2 were obtained from two sources. The time measurements were made during a study in which a RAB infusion was simulated. The dose-rate levels specified are the results from several measurements made by the institution's health physicist during patient treatments.

After completing infusion and flushing, the syringe is monitored together with the rest of the apparatus. From these measurements, the residual activity in the apparatus is calculated. It is usually less than 4.6 MBq (125 μCi) after infusing 1.1 TBq (30 mCi) of activity. On this basis, the only measurements of interest routinely taken are on the Buretrol. These are 0.5 mGy/h (50 mrad/h) and 1.5 mGy/h (150 mrad/h) at contact with the Buretrol when it contains 1.1 and 2.6 TBq (30 and 70 mCi), respectively. These measurements were made while a technician was doing the administration, which is sometimes done by a physician. Survey measurements were made with an Eberline®[5] Model ESP-1 survey instrument. The results are shown later in Table 2.1.

## 2.3 Abbreviated Description of Technique for the Infusion of Radiolabeled Antibodies at Institution #3

The observations focused on use of I-131 labeled antibodies. The RAB is prepared for intravenous infusion using a controlled-flow infusion pump.

### 2.3.1 Preparation and Infusion of RAB

The RAB solutions were prepared and drawn into 5-cc syringes in the radiopharmaceutical laboratory. Loaded syringes were placed in machined-to-fit lead shields which, in turn, were placed in lead boxes with removable tops. The carrying apparatus was placed on the bottom shelf of a radionuclide transport cart.

Two patient infusions were observed. The first patient received 4,070 MBq (110 mCi) of I-131 labeled antibody, M195, which was suspended in 3-cc of 25% human serum albumin. The patient previously had been prepared with an intravenous catheter connected to an infusion pump®[6]. The pump was programmed to infuse 70-cc of solution in 20 minutes. The usual infusion times vary from 20 to 60 minutes. The infusion pump was fed from a 250-cc drip bag with a Y connection allowing injection of the radionuclide into the bag and the flow of the material out of the bag upon demand from the pump. The bag was placed in a lead cylinder, which had a removable fitted cover with a clip on its bottom to hold the bag in position. The attending physician removes the syringe from the lead carrying case, inserts the needle into one arm of the Y connector and injects the solution into the bag (Figure 2.3).

[5] Eberline, P.O. Box 2108, Santa Fe, NM 87504.

[6] PANCRETEC PROVIDER MODEL 2000/4000 SERIES, San Diego, CA 92128

**Figure 2.3** One method of RAB infusion used at Institution #3. The RAB is being injected from a syringe into a plasma bag in a lead shield from which it is infused by pump into the patient.

During serial injections by the same physician, differences were noted in the technique used for manipulating the syringe. Thus, there are large variations in technique not only between individuals, but also by the same individual. This operation routinely takes 10 to 15 seconds per injection with 1 or 2 injections per treatment. The syringe is rinsed by drawing into it 10-cc of nonradioactive solution and then flushing it into the same injection port as in the initial injection of the radionuclide. After this, the physician grasps the top of the bag, shaking it several times to aid mixing. This operation takes about 5 seconds, after which the fitted cover is placed on the shielding cylinder and the infusion can begin. At this time, the reservoir contains 7,770 MBq (210 mCi), the sum of the first injection (4,070 MBq (110 mCi)) and the second (3,700 MBq (100 mCi)). Once the infusion began, everyone left the room and the patient was observed from the corridor through the open door. During infusion, the radiation level at the open door to the room was 5 μGy/h (0.5 mrad/h). After infusion, the tubing plus pump produced a dose rate reading of 400 μGy/h (40 mrad/h) at contact without the beta shield in place, and 80 μGy/h (8 mrad/h) at contact with the beta shield in place.

The second patient received 7,700 MBq (210 mCi) of I-131 labeled CC-49 antibody in 100-cc of 25% human serum albumin. The activity was initially contained in two syringes, each containing approximately 3-cc of solution. The techniques used were the same as described for the previous patient.

### 2.3.2 Measurements of Dose Rates

The major exposure to the hands of the attending physician occurred from the following activities:

(1) Removing the syringes from the shielded environment.

(2) Injecting the material into the drip bag.

(3) Shaking or kneading the bag to facilitate mixing.

Minor exposures could occur to either the attending physician or the nurse, who removes the pump head from the provider unit and coils the tubing, together with the bag, into the lead shield.

For both patients, radiation measurements were taken with a Keithley 36100 ionization chamber rate meter with the beta shield in place. For the first patient, readings indicated a radiation level of 32.8 mGy/h (3.28 rad/h) at the top of the shielding cylinder with the cover removed. The bag, at this time, contained 4,070 MBq (110 mCi) of the I-131 solution. With the cover of the lead shield in place, the readings at the top and the side of the cylinder were identical; i.e., 500 µGy/h (50 mrad/h) at contact, and 28 µGy/h (2.8 mrad/h) at 1 meter. After injection of the material in the second syringe, the reading at the top of the cylinder was 110 mGy/h (11.0 rad/h) with the cover removed. With the cover on the shield, the reading at contact with the top or side of the cylinder with the beta shield in place was 900 µGy/h (90 mrad/h) after the two injections, and 12 µGy/h (1.2 mrad/h) behind additional lead bricks placed around the shield during the infusion.

The syringes containing 3,700 MBq (100 mCi) I-131 produced dose rates of 80 mGy/h (8 rad/h) at contact with the instrument beta shield in place, and 110 mGy/h (11.0 rad/h) at contact without the beta shield. At 1 meter, the reading with the instrument beta shield in place was 270 µGy/h (27 mrad/h). When the syringes were in the shielded carrying case, the instrument reading was 170 µGy/h (17 mrad/h) at contact, and 2 µGy/h (0.2 mrad/h) at 1 meter, with or without the shield in place.

After completing the infusion, the pump head with its attached tubing is placed back in the shield with the empty bag. These materials resulted in a 6 µGy/h (0.6 mrad/h) dose rate at the surface of the lead shield. The results are shown later in Table 2.1.

## 2.4 Limitations of Institution Measured Doses for Estimating Doses Due to Exposures to RABs.

The following are the possible sources of error in assessing the dose to medical personnel.

(1) Dosimeters are routinely worn on the back of the finger, and thus, do not register beta-particle exposures on the hand or finger surfaces in contact with the radiation source.

(2) "Contact" measurements, as taken with ionization chamber instruments and used in the calculations, have the inherent problem that the effective center of the sensitive volume is not at the "contact" position of the front of the instrument. Corrections for this could be made, but were not possible within the time and budget constraints of this investigation. For example, for small sources of beta particles (e.g. < 1 mm), this correction factor for dose, averaged over 1 $cm^2$ at 7 mg $cm^{-2}$ depth in tissue, was about 150 times the open-window response for an Eberline Model RO-2/2A ionization chamber instrument (McWilliams et al., 1992). This instrument has a 208 $cm^2$ cylindrical collection volume and illustrates the importance of knowing and applying an appropriate correction factor when using this type of instrument for "contact" measurements.

(3) The quarterly dose may involve more than the one radioactive material and activities other than used for these observations.

## 2.5 Summary

An examination was made of some current techniques for administering RABs. Also, data were collected on administered activities, measured dose-rates for specific procedures, and reported quarterly doses. The study was carried out through correspondence, telephone discussions, and visits to selected institutions to observe and document the administration practices. The RABs were tracked from the radiopharmacy until after infusion into the patient. Information was specifically gathered on I-131 and Lu-177.

It was determined that personnel receiving hand exposures directly related to RAB infusions were 1) nuclear-medicine physicians, 2) nurses, and 3) in some cases, assisting radiopharmacy or health-physics technicians. It became apparent that great variability in techniques exists among institutions using the same RABs to treat the same diseases. These differences exist at every step of the procedure including delivery of the RAB to the individual making the infusion. This delivery may be in an unshielded syringe (transported within a protective lead shield), in a lead-shielded syringe (in a transport shield), or in a serum vial already contained in a lead shield with only the neck of the vial protruding. Infusions at the institutions visited were done either by gravity feed or with a peristalsis pump. Telephone discussions indicated some institutions use a hand-held syringe; however, such techniques were not observed at the three institutions for which data are provided.

Dose rates measured at three institutions are summarized in Table 2.1. Quarterly doses reported on hand and body dosimeters also are shown. With one exception, the infusion of the RABs appears to contribute a relatively small percentage of the measured quarterly exposure. The one exception is that when the unshielded syringe is handled by the physician who also manipulates the drip bag containing unshielded RABs. However, finger (ring) dosimeters are generally worn with the detector on the outer surface of the finger rather than on the palm side, which faces the source. Therefore, the ring dosimeter may have been a poor measure of maximum exposure to beta particles. Also, the finger dosimeters are generally worn only on the dominant hand.

**Table 2.1 Summary of activities, and doses measured or recorded at three institutions using radiolabeled antibodies.**

| | | | Radionuclide | | Syringe | | Reservoir | | Quarterly Meas. Dose, µGy | |
|---|---|---|---|---|---|---|---|---|---|---|
| Institution | Person | Operation/Hand | Elem. | Activity, MBq | Contact reading, µGy/h | Tm Ct, s | Ct Rd, µGy/h | Tm Ct, s | Hand | Body |
| 1 | Nurse | IIIa | Lu-177 | 1590 (43 mCi) | NA[1] | NA[1] | 550 | 25 | 300 | NR |
| | Nurse | IIIb | Lu-177 | 1590 (43 mCi) | NA[1] | NA[1] | 550 | 10 | 300 | NR |
| | Nurse | IIc | Lu-177 | 1590 (43 mCi) | NA[1] | NA[1] | 550 | 25 | 500 | 300 |
| 2 | Technician | I | I-131 | 1110 (30 mCi) | NA | NA | 500 | 20 | 20,500‡ | 400‡ |
| | Technician | I | I-131 | 2590 (70 mCi) | NA | NA | 1500 | 20 | ND | ND |
| 3 | Physician | Ia | I-131 | 4,070 (110 mCi) | 33 | 15 | NA | NA | see below | see below |
| | Physician | Ib | I-131 | 3,700 (100+ mCi) | 33 | 15 | 110** | 5 | 1300 | 900 |
| | Physician | IV | I-131 | 7,770 (220 mCi) | NA | NA | 55AF | 20 | 500* | 300 |

Operation/Hand:

a - right hand
b - left hand
c - both hands

I - Transfer of solution (syringe to bag, pump, or patient)
II - Disconnecting and disposal of apparatus
III - Controlling flow of solution during infusion
IV - Flushing of system

Ct Rd - Contact Dose Reading
Tm Ct - Time of Contact

NR - not received from institution
NA - not applicable (does not apply to that individual's task)
NA[1] - not applicable, syringe not used
AF - After flushing
ND - no dosimeter available
** - reservoir reading is sum of 2 injections 1a and 1b
‡ - Highest dose for any quarter in last 3 years. Right hand average/quarter over a 3-year period. Technician does radiopharmaceutical work and injections.

# 3 EXPERIMENTAL METHODS

The following were the specific objectives of this work:

(1) to measure the surface dose rates from radionuclides in polypropylene syringes of different sizes,

(2) to determine the geometric conditions related to handling syringes containing RABs which will keep doses to the skin of staff as low as reasonably achievable (ALARA), and

(3) to measure the attenuation of radiation by polypropylene, which is used in syringes.

Three different volumes were used in the syringes held by paraffin phantoms. In 3-cc syringes, the volumes were 0.5, 1.0, and 2.0 ml. In 6-cc syringes, the volumes were 1.0, 2.0, and 4.0 ml. In 12-cc syringes, the volumes were 2.0, 4.0, and 8.0 ml. The dose rates measured on the surface of syringes in this work are useful as a reference because they are the maximum dose rates possible. However, the relationship between dose to a ring badge and dose rate on the surface of a syringe is likely to be very dependent on geometry.

Measurements of dose rates were made with dosimeters on the fingers of phantoms to determine the best location to measure the maximum dose to the skin of the hand, and to allow the determination of correction factors to be applied to the measurements made on specific fingers for a typical geometry. The best representation of this particular geometry is shown in Figure 2.2. These correction factors may be estimated from the TLD measurements of dose at the surface of the syringes as described in Section 4. Gloves were not placed on the hands, but corrections to dosimeter readings can be made for gloves of known thickness using attenuation measurements in polypropylene given in Section 4.4

The concentrations of the solutions in the syringes were determined using a spectrometer with a high-purity germanium (HPGe) detector for the gamma emitters, and a liquid scintillation spectrometer for Y-90. The TLD reader was calibrated using an extrapolation chamber and a Cs-137 gamma-ray source of known activity.

Table 3.1 gives the characteristics of the radionuclides used in this work. Lu-176m and Lu-177m are contaminants in Lu-177. These did not present a problem in calibrating radioactive concentrations or dosimetry because the Lu-176m decayed to negligible levels during shipment and preparation of the Lu-177 for experiments. The low specific activity of the Lu-177m (compared to Lu-177) made it undetectable by gamma-ray spectrometry more than a week after the Lu-177 was produced.

Specifications on equipment and materials used in this work are given in Appendices 1 and 2. All electronic equipment was operating for not less than 24 hours before use. Syringes were filled to a maximum of two-thirds of capacity to preclude spills from inadvertently separating the plunger from the barrel. Activities used were kept as low as practicable.

Due to the variety of geometries employed by various practitioners and at various institutions, a single representative geometry was selected for phantom studies and supplemented by measurements of contact doses on syringes of various sizes (Section 4.5). The latter provide maximum dose-rate values for use in estimating worst case exposures for other geometries that may be of interest.

**Table 3.1 Characteristics of the radionuclides used in this work*.**

| Radionuclide | Physical half-life, hours | Maximum beta range, mg cm$^{-2}$ | Dose rate constants | | Primary Energy, keV | Photon: Abund., %/dis. |
|---|---|---|---|---|---|---|
| | | | Electrons and beta particles [1] | Exposure rate [2] | | |
| Y-90 | 64 | 1,100 | 1.49 E-13 | 0.293 [3] | | |
| Tc-99m | 6.01 | 19 | 2.58 E-15 | 4.39 | 141 | 89.1 |
| I-131 | 192 | 210 | 3.04 E-14 | 15.3 | 364 | 81.2 |
| Lu-177 | 161 | 160 | 2.35 E-14 | 1.25 [4] | 206 | 11.0 |
| Lu-176m [5] | 3.68 | | | | | |
| Lu-177m [6] | 3,862 | | | | | |

* After Barber *et al.*, 1991 (Weber *et al.*, 1989; Erdtmann and Soyka, 1979; ICRP, 1983)

[1] For electrons and beta particles. Units of numerals in this column are Gy kg Bq$^{-1}$ s$^{-1}$. Divide by 7.51 E-14 to obtain rad g $\mu$Ci$^{-1}$ h$^{-1}$.

[2] The units in this column are $\mu$C kg$^{-1}$ cm$^2$ MBq$^{-1}$ h$^{-1}$. Divide by 6.97 to obtain R cm$^2$ mCi$^{-1}$ h$^{-1}$. These constants exclude photons <20 keV.

[3] Based on the exposure rate from bremsstrahlung (Williams et al., 1989).

[4] Stabin, 1990.

[5] Produced with Lu-177 by thermal neutron capture in natural Lu-175.

[6] Produced with Lu-177 by thermal neutron capture in natural Lu-176.

## 3.1 Preparation of Phantoms

Dental impression material (Jeltrate®) was mixed with water at 4°C to extend its setting time. Since there is no standard way to hold the syringe during infusion, the geometries employed here are only representative ones. The author's hand (holding a syringe in an injection position) was immersed to the wrist in the mixture until it set at room temperature, but was still flexible enough so the hand could be removed without damaging the impression. The impression was then filled with paraffin at 80°C, and allowed to stand at room temperature for 4 to 16 hours, depending on the time of day the paraffin was poured. About 454 g (1 lb) of paraffin was used to mold each phantom. Then, the impression material was cut away from the paraffin hand (the phantom). The phantom was placed in an oven at 40°C for 10 minutes to soften it enough to replace the syringe used to mold it with a clean one.

Nine phantoms were made to hold 3-, 6-, and 12-cc syringes, each with the plunger positioned to hold one-third, one-half, and two-thirds of the syringe's capacity (see Figure 3.1).

## 3.2 Thermoluminescent Dosimeters (TLDs)

Doses were measured with extruded (3.2 x 3.2 x 0.89 mm) LiF TLDs (TLD-100, Solon Technologies, Inc.). The density of this material is 2.61 g cm$^{-3}$. Hence, the density-thickness of each TLD was 232 mg cm$^{-2}$.

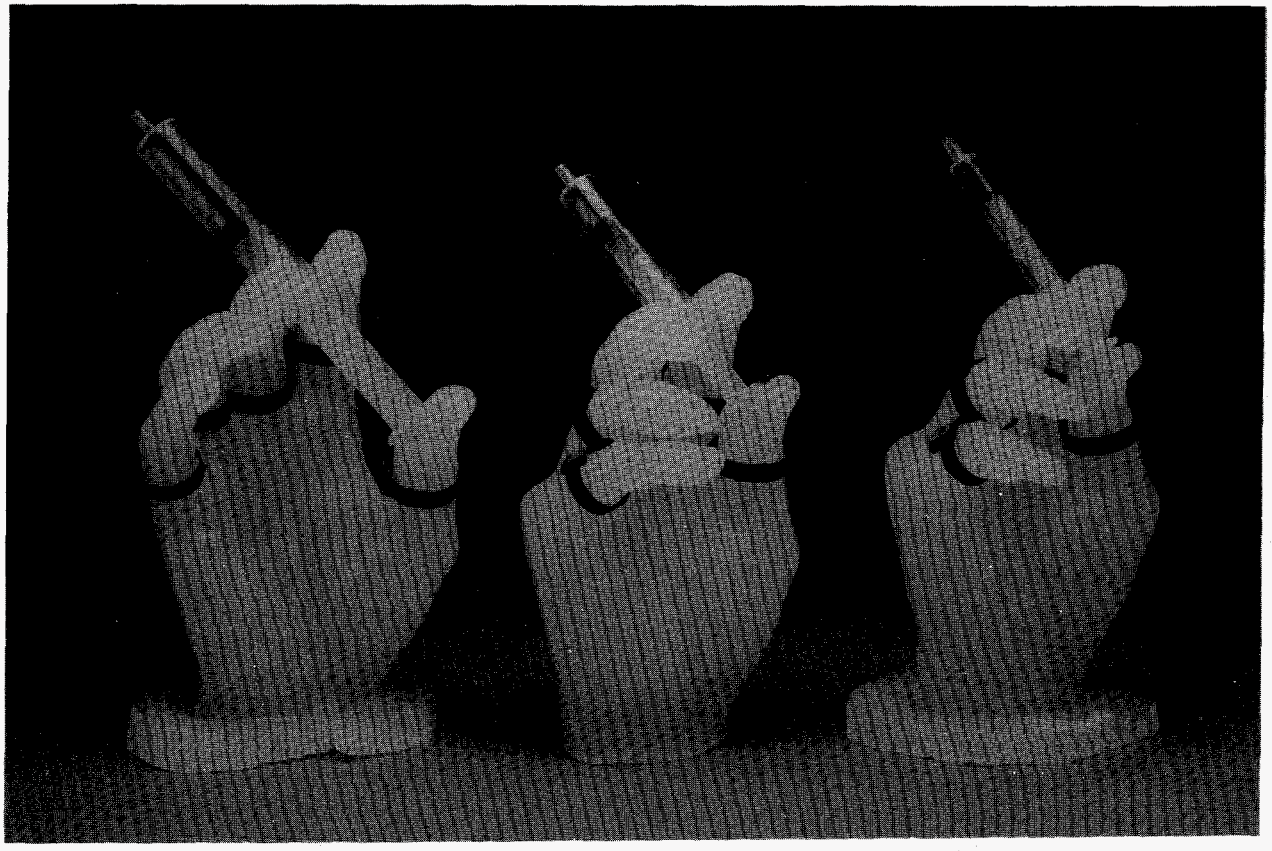

**Figure 3.1 Three paraffin phantoms with dosimeter rings, and syringes in exposure geometrics.**

A vacuum probe was used to handle TLDs and they were shielded from unwanted exposure and were covered to preclude ultraviolet light. Each TLD was stored and annealed in a separate receptacle in an anodized aluminum tray containing 100 indexed receptacles. All had the same production, storage, and annealing histories. The TLDs were annealed at 400°C for one hour, cooled to <50°C in <5 min on a block of steel, and annealed again at 100°C for two hours. The TLDs also were annealed at 100°C for 10 min just before they were read.

The 100°C- and 400°C-TLD annealing temperatures were confirmed with a Simpson Thermometer and a constantan thermocouple. The thermocouple readings and the oven readings agreed to within less than ±3%. The thermocouple calibration was confirmed in 4°C and 37°C incubators, and in boiling water (100°C).

Doses to TLDs were in the linear portion of the dose-response curve for LiF - less than 5 Gy (500 rads). The minimum dose to a TLD was less than 0.05 mGy (<5 mrad), and

the maximum dose was 45.7 mGy (4.57 rad). Most doses were in the range of 0.5 to 3 mGy (50 to 300 mrad).

All TLDs were exposed, then stored in the annealing tray until they were read. The dosimeters exposed to the radiation from a radionuclide were read on the same day, within 7 days after the first exposure.

## 3.3 TLD Reader

An encapsulated Cs-137 source of known activity (±5%) was used to expose TLDs from 0.62 mGy (62 mrad) to 45.4 mGy (4.54 rads). Measurements with an extrapolation chamber confirmed the activity of the source within ± 2%.

TLDs used to calibrate the TLD reader were exposed in 3-cc syringes wrapped in additional polypropylene to assure electron equilibrium around the TLD. The syringes were placed at known distances from the source and exposed for periods sufficient to produce doses in the TLDs that were in the range of those expected from experimental exposures.

The dose (D) to each TLD was calculated using the equation:

$$D = k \Gamma f A e^{-\lambda t} t' / r^2 \qquad (1)$$

where,

- D is the TLD dose
- k is a constant to justify the units
- $\Gamma$ is the exposure rate constant
- f is the f-factor for LiF
- A is the activity at the time of calibration
- e is the base of the natural logarithm
- $\lambda$ is the decay constant for the radionuclide
- t is the time from source calibration to exposure
- t' is the period of exposure
- r is the distance of the TLD from the source

The f-factor for the TLDs, which converts exposure in air to dose in LiF, was determined for 662 keV photons from the mass energy absorption coefficients published by Hubbell (1982).

The net thermoluminescence (TL) from exposed TLDs was graphed as a function of dose. The slope of the best-fit line of net TL as a function of dose on linear coordinates was used as the calibration factor to convert TLD readings to dose. A calibration factor was determined for each set of TLDs read.

The TLD reading cycle was 17 s at 100°C, 13 s from 101-239°C, and 11 s at 240°C.

## 3.4 Doses and Dose Rates on Phantoms

TLDs were placed in finger rings (Solon Technologies, Inc.) and covered with Scotch Magic Tape® (6.5 mg $cm^{-2}$) and Mylar® (0.88 mg $cm^{-2}$) for a combined thickness of 7.4 mg $cm^{-2}$. The loaded rings were placed on the phantoms with the TLD facing away from the outside of the hand on the index, middle, ring, and little fingers, and facing the palm on the thumb, as shown in Figure 3.1. These orientations reflected the maximum likely doses to each finger.

The distances between the TLDs and the mid-point of the radioactive solution was kept as short as possible, compatible with secure positions on the human hand. The tips or middles of fingers are unsuitable locations because they would interfere with dexterity, and dosimeters could slip from fingers, and be lost; all rings were placed close to the knuckles.

The palm and back of the phantom were excluded because of the impracticality of wearing dosimeters there. Further, the distance from the source, and attenuation by the phantom would have required much higher levels of activity, and the exposure

times would have been incompatible with those required to obtain good readings on the fingers.

A single stock solution for each radionuclide was prepared in a volume of about 30 ml. A 12-cc syringe in a syringe shield was used to fill each syringe on each phantom to the desired volume from the stock solution. This method of filling syringes was used because the syringes on the phantoms were stationary, and also to minimize handling of unshielded syringes. A single bubble at the tip of each syringe represented less than 10% of the volume to which each syringe was filled.

The period of exposure was from the time of filling a syringe until the time the rings were removed from the phantom after 17 to 48 hours, depending on the radionuclide being used. Exposure periods were selected to yield easily measured TLD doses (10s of mGy). TLDs were removed from the rings, returned to their assigned locations in the TLD tray, covered, and stored behind a shield until they were read.

## 3.5 Measurements of Attenuation

Attenuation was measured with polypropylene to determine the effects of both small changes in distance from the surface of syringes, and the attenuation of beta particles and secondary radiation. These measurements were made using polypropylene absorbers (see Figure 3.2) made from the casings in which sterile syringes were supplied. Attenuation by glass was not measured because glass syringes are rarely used to administer radiopharmaceuticals.

Attenuation measurements were made by placing a syringe in a plastic cradle on the counter top (see Figure 3.2). A bare TLD was exposed directly on the syringe over the center of the radioactive volume in the syringe. Sequential, additional layers of polypropylene were placed over the barrel of the syringe, and a TLD was exposed for each thickness used. Exposure times ranged from 0.1 to 1.4 h, depending on the radionuclide and activity in the syringe.

## 3.6 Distribution of Dose Rate on Syringes

The surface dose rates on syringes were measured by placing a bare TLD directly on a syringe at the locations indicated in Figure 3.2. These exposures required minutes to hours, depending on the radionuclide being used.

## 3.7 Initial Dose Rates

Dose rates varied during TLD exposures due to activity decay, therefore, the measured dose (D) at the beginning of an exposure was used to obtain a dose rate ($D_0$). Comparison of the dose rate with activity present at that time yielded a value of the dose-rate coefficient (dose rate per unit of activity).

The dose rate ($D_0$) at the beginning of each TLD exposure was calculated from the equation:

$$D_0 = \lambda D / (1 - e^{-\lambda t}) \qquad (2)$$

where,

$D_0$ is the dose rate at t = 0
$\lambda$ is the decay constant for the radionuclide
D is the dose accumulated in time t

This equation enabled us to directly compare results for the different radionuclides.

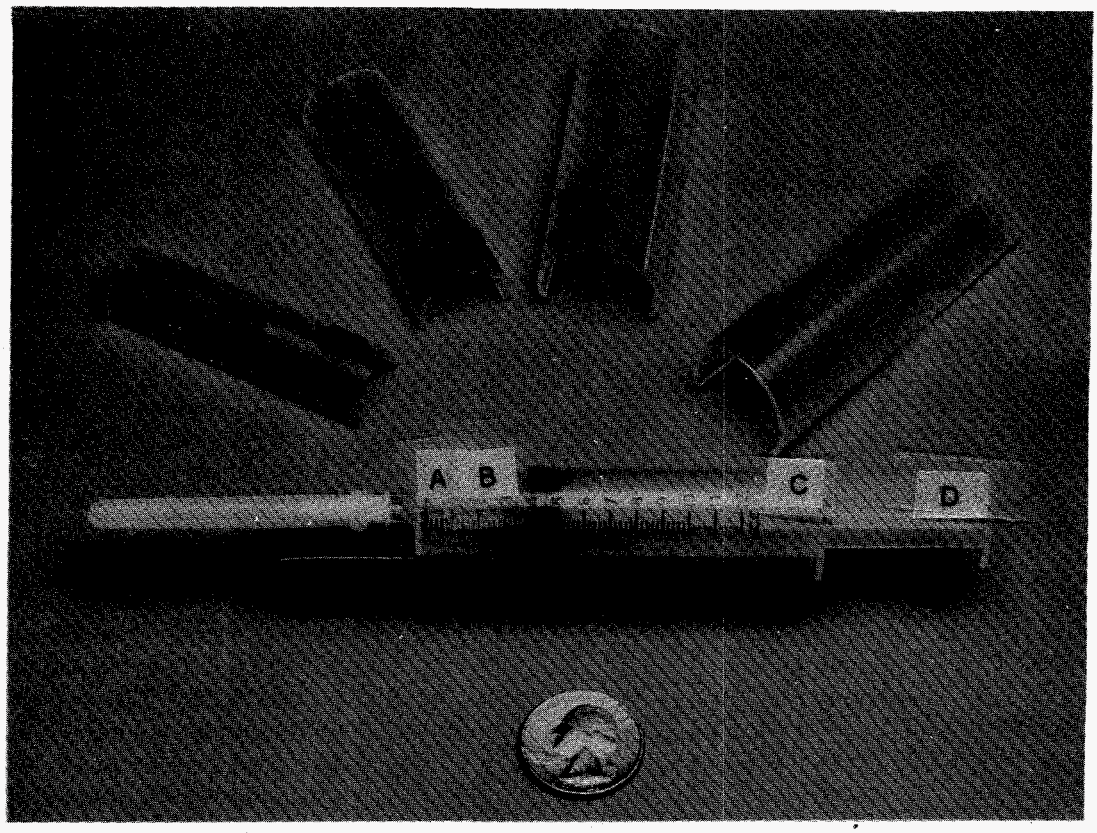


**Figure 3.2 Examples of polypropylene absorbers and locations of TLDs on the surface of syringes. The TLDs are visible just below the letters A, B, C, and D. Attenuation measurements were all made at position B.**

## 3.8 HPGe Spectrometer and Solution Calibrations

The standard for calibrating the high-purity germanium (HPGe) spectrometer for energy and efficiency was a mixture of Am-241, Eu-152, and Cs-137 in 10 ml of solid plastic in a 20-cc liquid scintillation vial. The calibration of the standard, dated 1 June 1990, was traceable to the National Institute of Standards and Technology (NIST). The uncertainty in the activity of the standard was ± 7%. The standard (and aliquots from stock solutions in the same geometry) were counted 10 cm from the detector.

The full-peak efficiency (counts/photon after subtraction of background and Compton continuum) of the spectrometer was determined as a function of energy, using the energies and photon abundances (percent/disintegration) given in Table 3.1. Table 3.2 lists the photon energies, abundances, and efficiencies used to determine the activity concentration in Tc-99m, I-131, and Lu-177 stock solutions. The photon abundances were taken from Erdtmann and Soyka (1979). Efficiencies for energies below 122 keV were determined from a log-log graph of efficiency as a function of energy; efficiencies above 122 keV were determined from the equation that best fit the same graph.

A micropipette, accurate to ±3%, was used to transfer 0.020 ml aliquots from stock solutions to 20-cc liquid scintillation vials containing 10 ml of water. These samples were stored until each could be counted without

coincidence losses; i.e., less than about 37 kBq (1 $\mu$Ci). The activity determined by HPGe spectrometry was used to calculate the radioactive concentration of Tc-99m, I-131, and Lu-177 in each syringe at the time of exposure.

## 3.9 Liquid Scintillation Counting for Y-90

The efficiency of liquid scintillation counting is a function of energy for maximum beta-particle energies up to about 150 keV (Dyer, 1980). At higher energies the efficiency approaches 100%. The efficiency for beta particles from P-32 (1.7 MeV max.) was observed to be 95%. Even when 8 ml of urine are added to 12 ml of liquid scintillator, the efficiency for detecting P-32 beta particles declines to only 90% due in part to dilution and in part to quenching of the scintillator by the urine (Bell, 1980). Efficiencies of 98 and 99 percent have been reported for Sr-90 and Y-90, respectively (Coursey and Calhoun, 1980). Hence, this was the method chosen to calibrate the Y-90 stock solution.

The efficiency of the liquid scintillation spectrometer was confirmed with a P-32 solution from NIST. Aliquots of 0.020 ml were taken from the stock solution and added to 20 ml of Ultama Gold® liquid scintillator. The detection efficiency was 99 ± 3%.

## 3.10 Extrapolation Chamber Measurements

An extrapolation chamber was used to measure dose rates from the Cs-137 source and a Sr-Y-90 eye applicator centered 10 cm from the chamber window. The latter source was used to confirm that the TLD reader calibration with Cs-137 gamma rays applied to beta-particles from Y-90. The activities of the Tc-99m, I-131, and Lu-177 in syringes were too low to measure dose rates with the extrapolation chamber.

Dose rates were measured 10 cm from the window of the chamber to assure uniform irradiation of the sensitive volume of the chamber. The diameter of the collecting electrode was 3.003 cm. These dose rates were used as the basis for calibrating the TLD reader.

The extrapolation chamber window was 2.62 mg $cm^{-2}$ of polyethylene terepthalate (Hostaphan®) coated with graphite. The collecting electrode was perspex (Plexiglas®) coated with graphite.

Plate separations of 0.5, 1.0, 2.0. 3.0, and 4.0 mm at a constant bias voltage of 20 V were used to measure charge accumulation as a function of time. Measurements were converted to ionization current (charge/time) and graphed as a function of plate separation. The slope of the best-fit line to this graph is proportional to dose rate. The dose rate in air at the surface of tissue-equivalent plastic is given by the following equation (Ahmed and Barber, 1989):

$$D = 1.03 \times 10^{-4}\, b(T/P) \qquad (3)$$

where,

D is the dose rate, Gy $s^{-1}$
b is the slope of the graph, pA $mm^{-1}$
T is the lab temperature, °K (i.e., 273 + °C)
P is the lab atmospheric pressure, mm Hg.

**Table 3.2 Photon energies, abundances, and detection efficiencies for the HPGe spectrometer.**

| Radionuclide | Energy, keV | Abundance, percent[1] | Efficiency: counts/photon | Efficiency: C.V.[2], % |
|---|---|---|---|---|
| Am-241 | 59.5 | 36.3 | 0.00545 | 3.8 |
| Eu-152 | 122 | 29.2 | 0.00552 | 1.2 |
| | 244 | 7.62 | 0.00311 | 4.6 |
| | 344 | 27.0 | 0.00209 | 1.6 |
| Cs-137 | 662 | 84.6 | 0.000980 | 2. |
| I-131 | 364 | 81.2 | 0.00192 | <3 |
| Lu-177 | 208 | 11.0 | 0.00331 | <3 |
| | 250 | 0.21 | 0.00274 | |
| Tc-99m | 141 | 89.1 | 0.00495 | <3 |

[1] From Erdtmann and Soyka (1979).
[2] Coefficient of variation for repeated measurements, $100(\sigma_{n-1})/(\text{average efficiency})$.

## 3.11 Corrections to TLD Measurements for Estimation of Skin Dose in Contact with the Syringe Barrel

One consideration with measuring the dose from syringes to the TLDs is that the dose is deposited in the entire TLD volume. This presents little difficulty with the dose deposited from photons since the absorbed dose changes very little over the TLD volume. However, it presents a larger difficulty if the dose from β particles at a certain depth in the TLD material is desired, since the absorbed dose from β particles changes significantly over the volume of the TLD.

For the geometry studied here, estimates were made of the maximum skin dose that personnel administering a radiopharmaceutical would receive. This would occur if the syringe containing the radiopharmaceutical were held at the middle of the solution volume, TLD position "B" in Figure 3.2.

### 3.11.1 Corrections to TLD Measurements for Skin Dose from Emitted Photons

The dose deposited in a LiF TLD dosimeter differs from that deposited in an equal mass of tissue or skin. The dose results from (a) secondary electrons ejected from the polypropylene syringe's walls and the solution in the syringe, and (b) secondary electrons produced within the detector or tissue by photon interactions. Due to the greater number of electrons per gram of skin (or tissue) compared to LiF, the dose from both processes is greater in skin than in LiF.

For electrons, the relative stopping power of skin compared to LiF is about 1.24 over the electron energy range from 20 keV to 2 MeV (ICRU, 1992). This causes the skin dose

from secondary electrons coming from the syringe walls to be about 24% higher than in the TLD dosimeter.

The relative TLD and skin doses, due to photon interactions directly in TLDs and skin, are proportional to the energy absorption coefficients, which vary with photon energy. To adjust for differences in this portion of the dose to each medium, photon emissions were weighted for yield (Bq/s) and energy, to arrive at a weighted average for TLD and skin. Table 3.3 summarizes the data used and the results of this calculation. For each photon energy, the ratio of absorption coefficients for skin and LiF was calculated (column 6), and also, the products of photon energy and emission rate (column 7). The fraction of total photon energy emitted at each energy was then calculated from the ratio of the energy and emission product to the total energy emitted (the entry in column 7 divided by the sum of all products listed in column 7). For each photon energy, this fraction (column 8) was multiplied by the ratio of absorption coefficients for skin and LiF (column 6) to arrive at the weighted ratios listed in column 9. The sums of these weighted ratios are also shown in column 9; they were 1.17 for Tc-99m, 1.24 for I-131, and 1.13 for Lu-177.

For these three isotopes, the dose is due mainly to direct photon interactions ((b) above). Thus, skin dose at 7 mg $cm^{-2}$ depth is estimated as higher than the average in the TLD detectors by an amount equal to either (a) 24%, if the dose is dominated by secondary electrons from the syringe walls, or (b) 13 to 24%, if the dose is due primarily to secondaries produced in the tissue. An approximate average of these values (20%) was used to adjust measured TLD doses to dose at 7 mg $cm^{-2}$ depth in tissue because this depth was in the transition region of secondary electron buildup.

### 3.11.2 Corrections to Skin Dose from Emitted Beta Particles

For Y-90, skin dose is due primarily to emitted beta particles. The TLD detectors were 0.89 mm thick, had a density of 2.61 g/cc, and stopping power for electrons about 0.8 times that for water (ICRU, 1984). The attenuation in TLD would, therefore, be equivalent to that in 186 mg $cm^{-2}$ (0.089 x 2.61 x 0.8) of water (or skin). This attenuation leads to a larger dose at shallow depths than the average dose, which is obtained from the TLD readout.

The dose at 7 mg $cm^{-2}$ depth in tissue was estimated using the VARSKIN MOD2 code (Durham, 1992) to calculate the ratio of average dose over a 1 $cm^2$ area at depth 186 mg $cm^{-2}$ in skin to dose at 7 mg $cm^{-2}$ in skin when exposed to disk, slab, and spherical sources containing Y-90.

For the spherical geometry, a diameter equal to the height of the solution in the syringe was used. The cylindrical geometry was a right circular cylinder of diameter and height equal to the solution's height in the syringe. The slab geometry was a slab of length and width equal to the solution's height, and thickness equal to the inner diameter of the syringe. Each geometry had a 1-mm thick cover of density 0.9 to simulate the walls of the polypropylene syringes.

In each case, the ratio of dose at 7 mg $cm^{-2}$ to dose averaged over 186 mg $cm^{-2}$ of tissue was 1.7. The product of this dose ratio and the factor 1.24 for the relative electron stopping power in skin compared to LiF yields a total adjustment for Y-90 of 2.1 (1.7 x 1.24) for dose to skin at 7 mg $cm^{-2}$ depth compared to the dose to LiF dosimeters in contact with the walls of the syringes. These values can be compared to correction factors of 2.36 to 4.39 for beta spectra inside a nuclear power plant normally or isotropically incident, respectively, on 240 mg $cm^{-2}$ TLDs

# 4 EXPERIMENTAL RESULTS

## 4.1 Calibration of TLD Reader

The results of all calibrations for the TLD reader for Cs-137 gamma rays are shown in Figure 4.1 with ±5% error bars. The same data for doses less than 12 mGy (1.2 rad) are presented in Figure 4.2 to show the variation of observations for these lower doses. The average slope (±1 standard deviation) from 10 independent calibrations of the reader was 51.3 ± 1.4 $\mu$Gy/TL (5.13 ± 0.14 mrad/TL) where TL represents light output in arbitrary units; i.e., the coefficient of variation expressed in percent ($100\sigma_{n-1}$/ mean) was 2.7%. The uncertainty associated with individual calibrations for exposures with a specific radionuclide are believed to be somewhat smaller.

The response of the TLD reader to beta particles from Sr-Y-90 is compared with its response to Cs-137 gamma rays in Figure 4.3. The slope of the beta-particle calibration graph is 5.6% higher than that of the gamma calibration graph i.e., the thermoluminescence (TL) per unit dose is lower for beta particles. Hence, the reader calibration factors for Y-90 beta particles and Cs-137 gamma rays are the same within less than ±5.6% (and probably within ±3%)

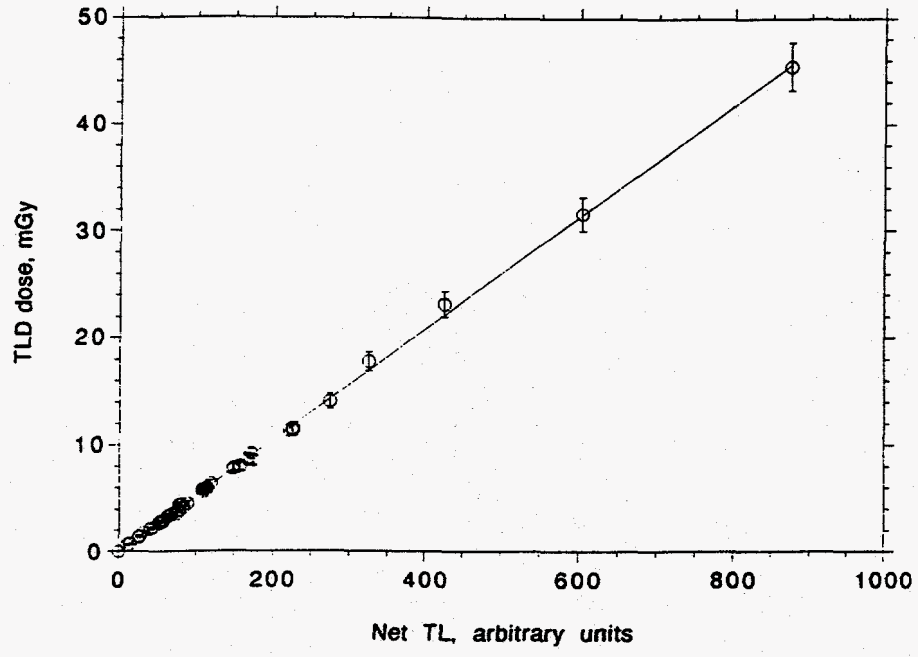


**Figure 4.1 Combined calibration data with ± 5% error bars for the TLD reader for TLD-100 dosimeters exposed to Cs-137 gamma rays.**

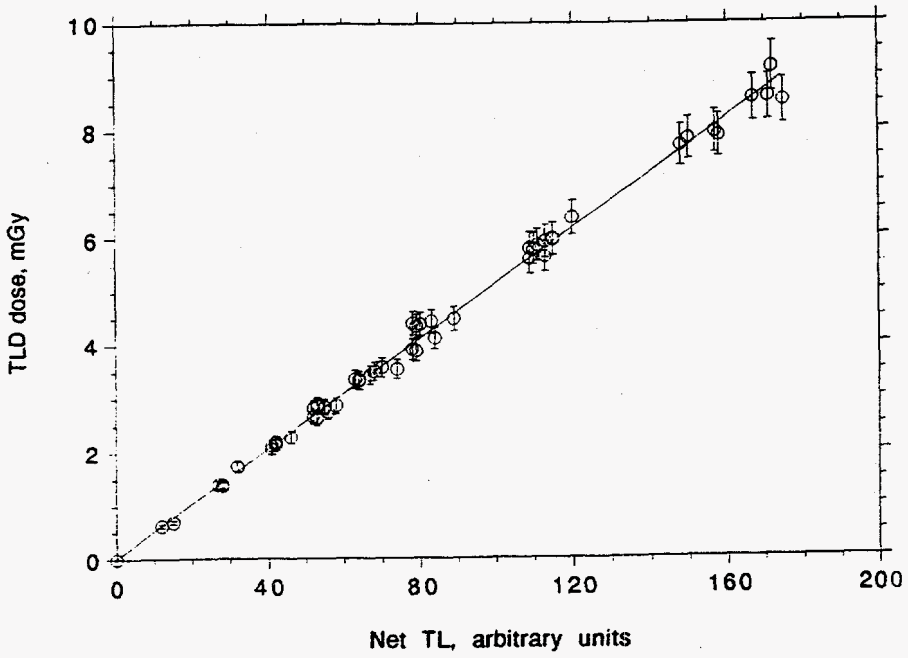


**Figure 4.2 Combined calibration data with ± 5% error bars for the TLD reader for TLD-100 dosimeters exposed to doses less than 10 mGy (1 rad).**

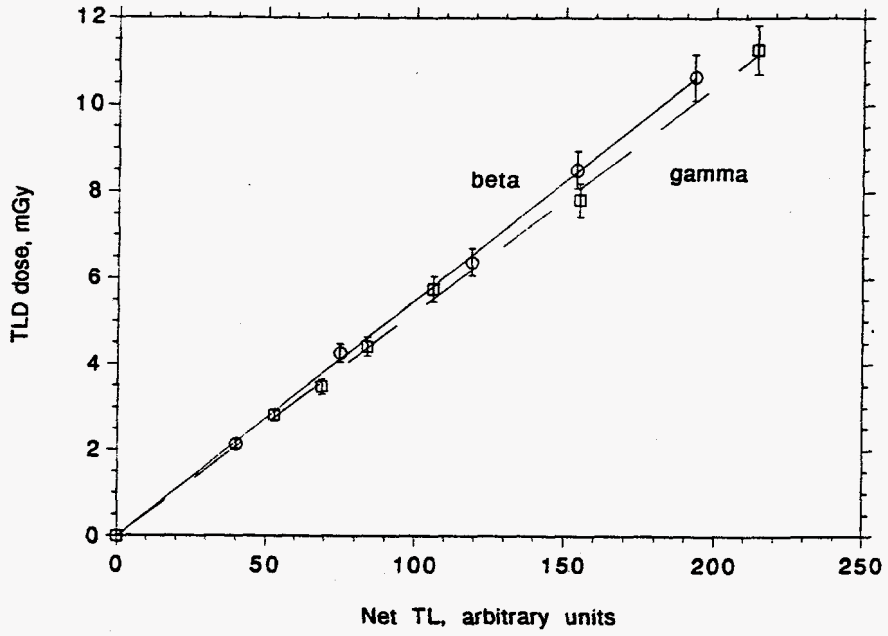


**Figure 4.3 Comparison of the Sr-Y-90 and Cs-137 calibrations for the TLD Reader. The error bars are ± 5%.**

## 4.2 Dose Rates on Phantoms

The dose rates to the dosimeters on the phantoms are given in Figures 4.4 through 4.7. Except for Y-90 exposures with a 3-cc syringe containing 2 ml, dose rates on the middle finger are highest for all the syringe sizes, volumes, and radionuclides used, and dose rates decreased with distance from the middle finger. The reason for the exception is unknown; it may reflect an experimental error.

The dose rates from Y-90 are much higher than those from the photon emitters, and the highest dose rates for the middle finger were observed for the smallest volume of solution in a given size of syringe. The smaller syringes also had the greater dose rates, attributed to greater self-absorption associated with larger volumes of solution. Also, the dose rates for Y-90 are less symmetrical about the middle finger than the dose rates for β emitters with a larger photon component. This difference is attributed to greater attenuation of the beta particles by the fingers on the phantom.

For the photon emitters, the dose rates decrease rather symmetrically with distance from the middle finger, and the highest dose rates are observed for the smallest syringe. The pattern with respect to volume in a syringe is more erratic than in the case of Y-90. In all cases for I-131, the 3-cc 2 ml syringe had the highest rates. The Lu-177 3-cc 0.5 ml syringe is the highest overall. The Tc-99m 3-cc 2 ml response increases, relative to 1 ml, with greater distance.

## 4.3 Distances on Phantoms

Table 4.1 gives the distances from the center of volumes in syringes to dosimeter positions on the phantoms. As the size of the syringe increases, the distances from the center of the solution to the dosimeters increase, and the expected dose-rate coefficient (mGy $s^{-1}$ $TBq^{-1}$) decreases.

The ratios of the squares of the distances using the middle-finger location (the location of highest dose rate on the phantoms) as the reference are given in Table 4.2. The middle-finger location of a dosimeter (MO) was closest to the solutions in the syringes. The thumb (TP) and little-finger (LO) locations were about equidistant from the solutions. Similarly, the ring- and index-finger locations were about equidistant from solutions.

The dose rates on the index finger compared to those on the middle finger were proportional to the inverse square of the distance from the middle finger. Dose rates at other locations on the phantoms were less than those predicted on the basis of dose rates to the middle finger by the inverse square of the distance from the source. Hence, the observed dose distributions are attributable to factors other than distance (e.g., distributed as opposed to point sources, self-absorption in the solution, orientation of the TLD with respect to the source, attenuation by the syringe, and attenuation by fingers). The smallest ratio of squares was 0.40 for the thumb, with a 12-cc syringe containing 8 ml of solution. That is, none of the finger dose rates would be larger than 2.5 times the dose rate to the middle finger if distance were the only consideration in the dose distribution on the hand for this particular geometry.

**Table 4.1 Distances from the center of radioactive volumes in syringes to TLD dosimeters on phantoms.**

| Syringe size, cc | Volume in syringe, ml | Distance (cm) to the TLD on: | | | | |
|---|---|---|---|---|---|---|
| | | LO[1] | RO | MO | IO | TP |
| 3 | 0.5 | 9 | 7 | 6 | 7 | 8.5 |
| | 1.0 | 9 | 7 | 6 | 7 | 8.5 |
| | 2.0 | 8 | 6 | 5.5 | 6.5 | 8.5 |
| 6 | 1.0 | 9.5 | 7 | 6.5 | 7.5 | 9.5 |
| | 2.0 | 9.5 | 7 | 6.5 | 7.5 | 9.5 |
| | 4.0 | 8.5 | 7.5 | 7 | 7.5 | 10 |
| 12 | 2.0 | 10 | 8 | 7 | 8 | 10 |
| | 4.0 | 10.5 | 8 | 7.5 | 8 | 10.5 |
| | 8.0 | 10 | 7.5 | 7 | 8 | 11 |

[1] LO = little finger, outside
RO = ring finger, outside
MO = middle finger, outside
IO = index finger, outside
TP = thumb, palmside

**Table 4.2 Ratios of squares of distances from the center of radioactive volumes in syringes to TLD dosimeters on phantoms with the middle finger as the reference (MO location distance/other location distance).**

| Syringe size, cc | Volume in syringe, ml | Ratio of the squares of distances: | | | | |
|---|---|---|---|---|---|---|
| | | LO[1] | RO | MO | IO | TP |
| 3 | 0.5 | 0.44 | 0.73 | 1.0 | 0.73 | 0.50 |
| | 1.0 | 0.44 | 0.73 | 1.0 | 0.73 | 0.50 |
| | 2.0 | 0.47 | 0.84 | 1.0 | 0.72 | 0.42 |
| 6 | 1.0 | 0.47 | 0.86 | 1.0 | 0.75 | 0.47 |
| | 2.0 | 0.47 | 0.86 | 1.0 | 0.75 | 0.47 |
| | 4.0 | 0.68 | 0.87 | 1.0 | 0.87 | 0.49 |
| 12 | 2.0 | 0.49 | 0.77 | 1.0 | 0.77 | 0.49 |
| | 4.0 | 0.51 | 0.88 | 1.0 | 0.88 | 0.51 |
| | 8.0 | 0.49 | 0.87 | 1.0 | 0.77 | 0.40 |

[1] LO = little finger, outside
RO = ring finger, outside
MO = middle finger, outside
IO = index finger, outside
TP = thumb, palmside

## 4.4 Measurements of Attenuation

The results of measurements of dose rates as a function of added absorbers on syringes are given in Figures 4.8 through 4.11 for Y-90, Tc-99m, I-131, and Lu-177, respectively. The error bars on the figures are ±10% to allow for uncertainty attributable to positioning and reading the TLDs. The slopes of the graphs for the photon emitters (Figures 4.9 to 4.11) are nearly independent of the volumes of the solutions in the syringes. The measurements for Y-90 were made with only the largest syringe containing the largest volume (8.6 ml).

The decrease in relative dose rate with thickness of added absorber (polypropylene) is attributable to both attenuation of the radiation by the absorber and increasing distance of the dosimeter from the radioactive solution in the syringe as absorbers were added. For example, the half-value layer for 8.6 ml of Y-90 solution in a 12-cc syringe (Figure 4.8) is about 0.8 mm, which is less than the half-value layer expected for unfiltered Y-90 beta particles, approximately 2 mm of water (Berger, 1971). The half-value layers for Tc-99m (≈ 2.3 mm), I-131 (≈ 2.8 mm), and Lu-177 (≈ 2.8 mm) are all at least a factor of ten larger than is expected from the beta particles emitted by these sources.

This demonstrates that dose from these latter three sources is primarily due to phantom interactions. The lower energies of beta particles emitted by these sources are effectively absorbed into the solution and walls of the syringe.

Another important observation made is that dose rate was significantly reduced with the addition of small amounts of polypropylene on the syringes.

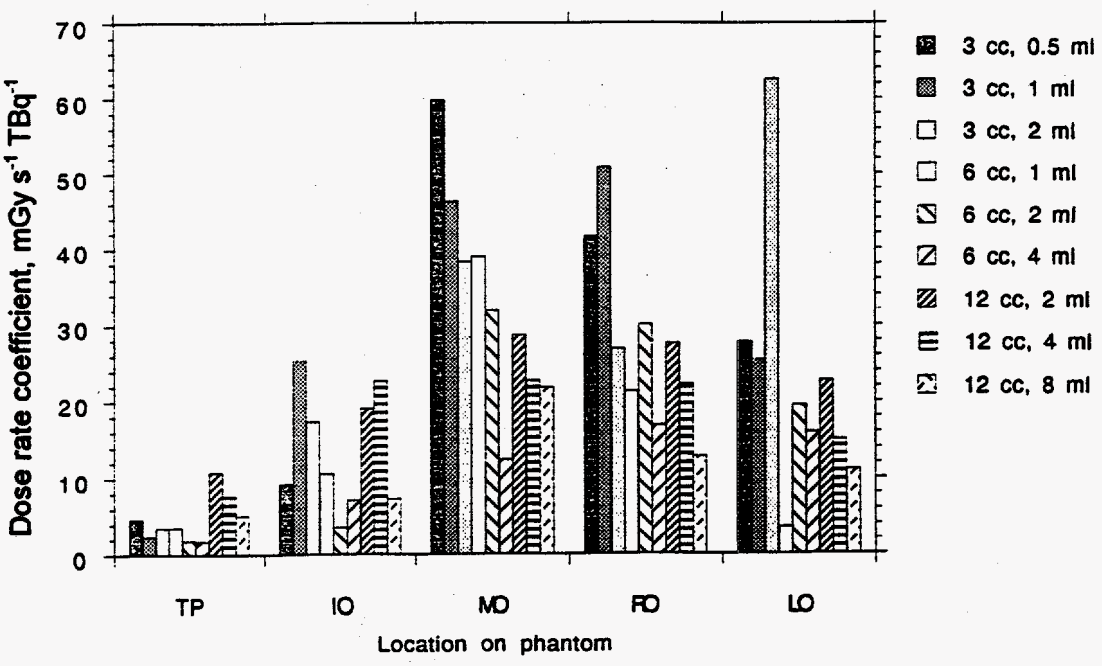


**Figure 4.4 Finger dose rates per TBq from different volumes of Y-90 in 3-, 6-, and 12-cc syringes. See Table 4.2 for definitions of locations on phantom.**

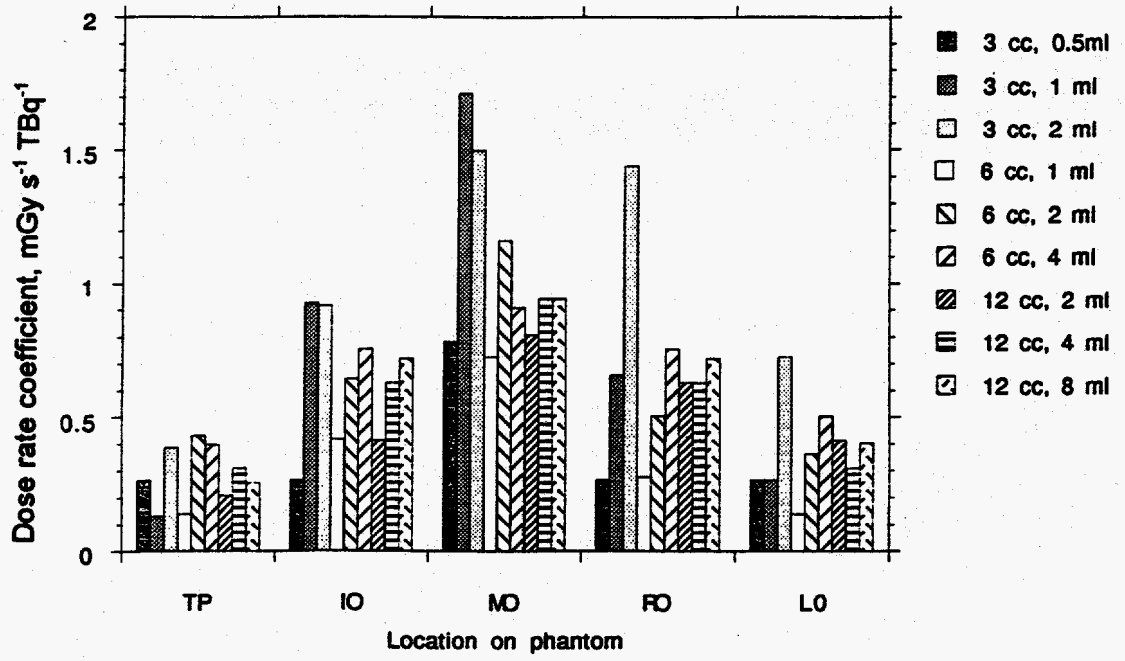


**Figure 4.5 Finger dose rates per TBq from different volumes of Tc-99m in 3-, 6-, and 12-cc syringes. See Table 4.2 for definitions of locations on phantom.**

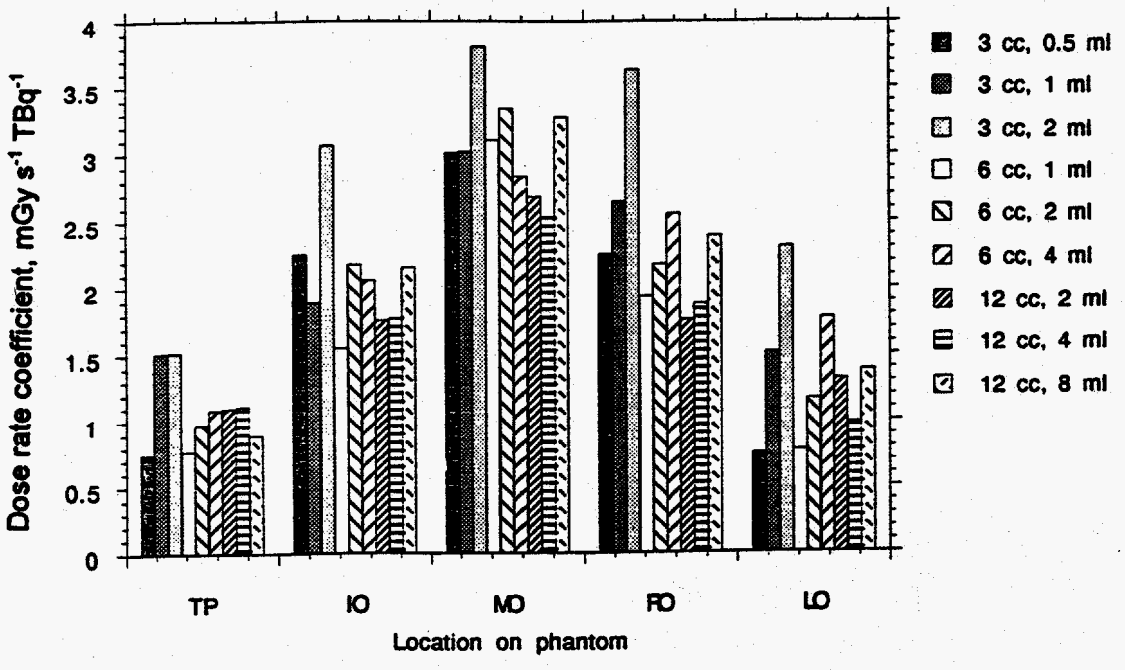


**Figure 4.6 Finger dose rates from different volumes of I-131 in 3-, 6-, and 12-cc syringes. See Table 4.2 for definitions of locations on phantom.**

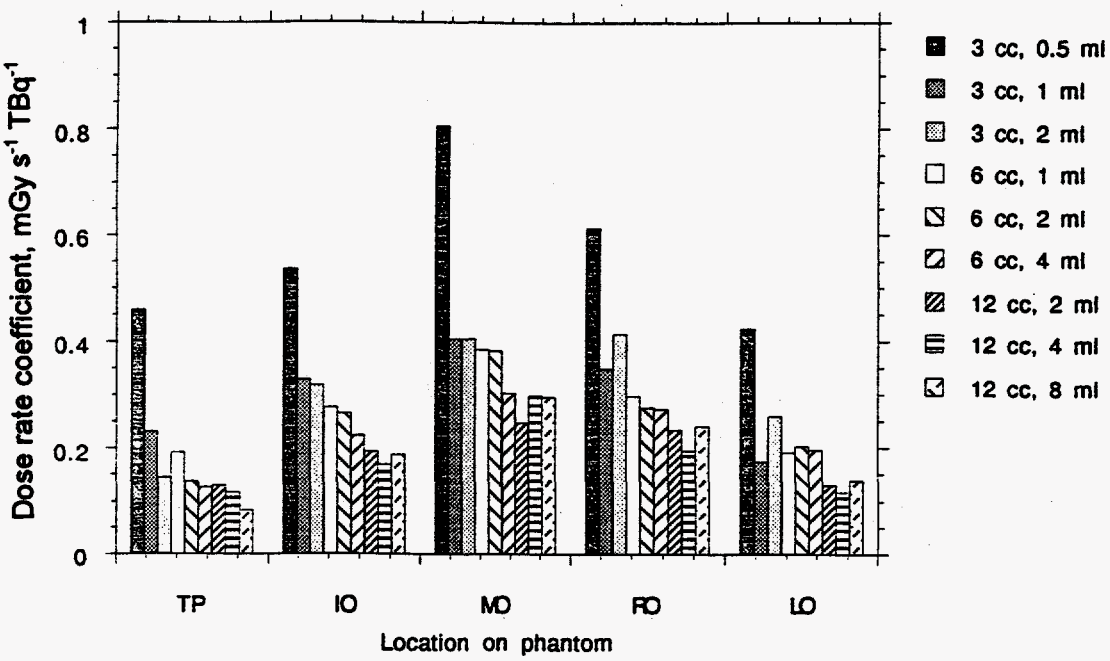


**Figure 4.7 Finger dose rates per TBq from different volumes of Lu-177 in 3-, 6-, and 12-cc syringes. See Table 4.2 for definitions of locations on phantom.**

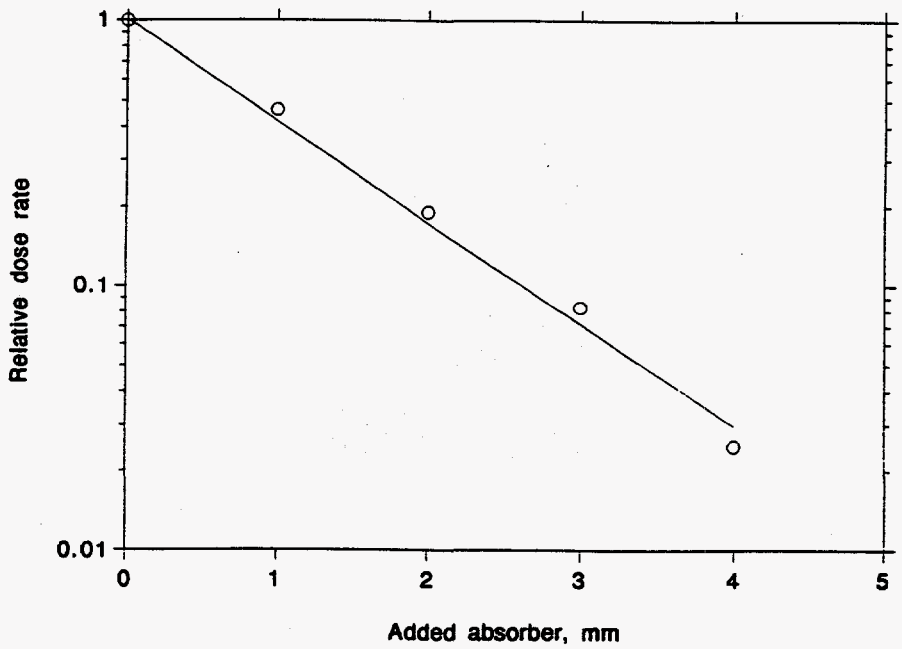


**Figure 4.8 Relative dose rate as a function of polypropylene thickness on a 12-cc syringe containing 8.6 ml of Y-90.**

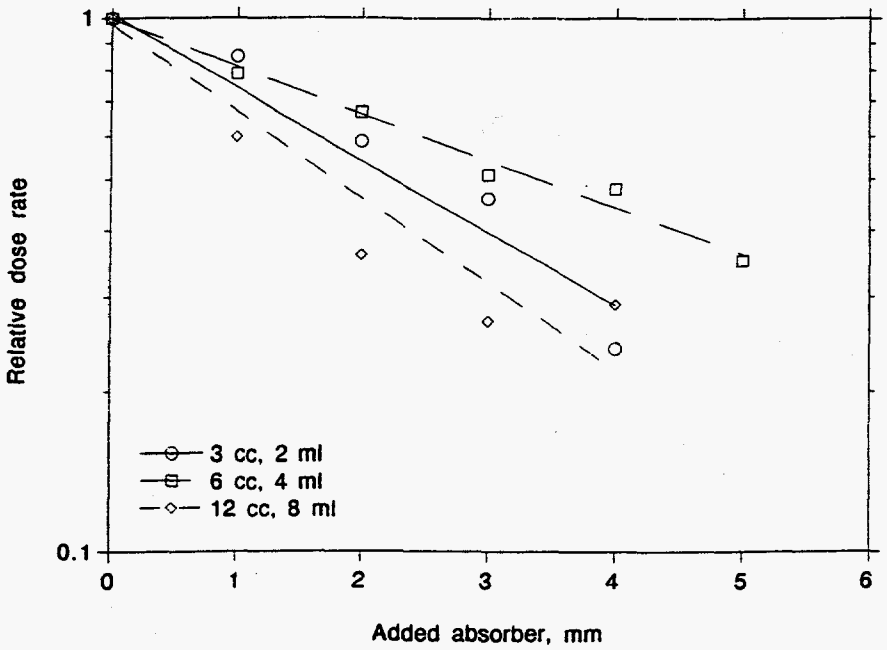


**Figure 4.9 Relative dose rate as a function of polypropylene thickness on syringes of different sizes containing different volumes of Tc-99m.**

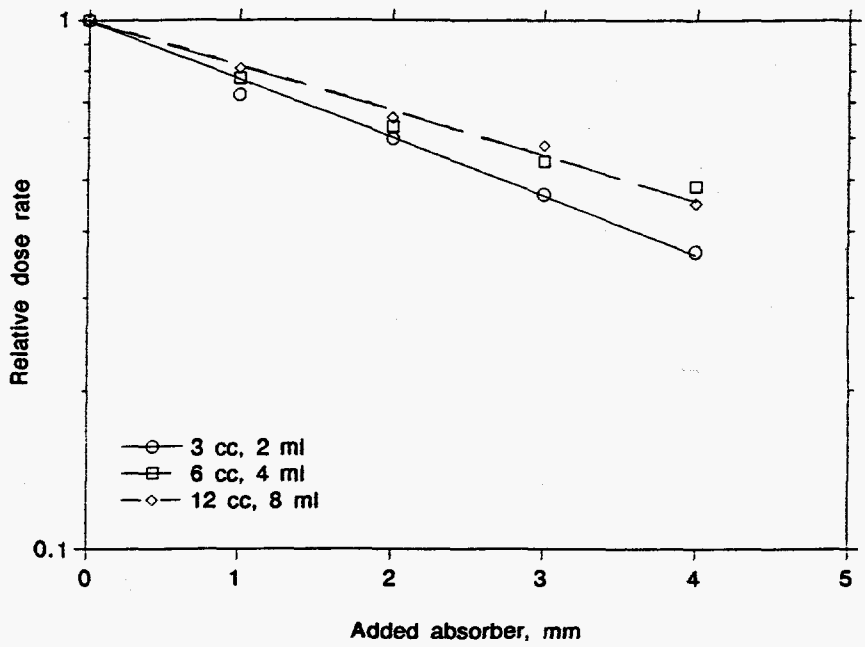


**Figure 4.10 Relative dose rate as a function of polypropylene thickness on syringes of different sizes containing different volumes of I-131.**

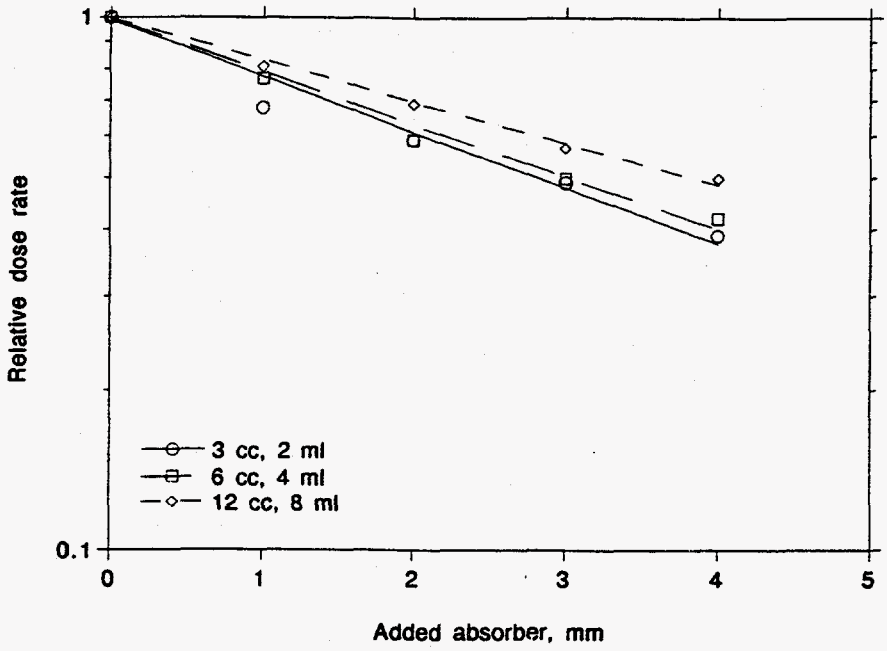


**Figure 4.11 Relative dose rate as a function of polypropylene thickness on syringes of different sizes containing different volumes of Lu-177.**

## 4.5 Distribution of Dose Rate on Syringes

As the volume in a syringe increases, the surface dose rate per unit of activity decreases due to self-absorption and changes in geometry with respect to the point of measurement. However, the actual dose rate will increase with volume for a given concentration of radioactive material because the amount of activity in a syringe will increase with volume.

The dose rates for Y-90 are much greater than those for the other radionuclides at positions A and B, but they decrease more rapidly with distance from these positions than for the other radionuclides. The dose rates for I-131 are lower than those for Y-90 at positions A and B, but the dose rates for I-131 at position C are somewhat higher because of the photons it emits. Except for Y-90, the highest dose rates at positions A and B were from I-131. The dose rates from Lu-177 are somewhat lower than those from Tc-99m.

## 4.6 Ratios of Syringe TLD/ Finger TLD Dose Rates

Since TLD dosimeters mounted on fingers, such as shown in Figure 3.2, do not measure the higher dose that may be received when the tips of fingers touch the surfaces of a syringe containing radiolabeled antibodies, it is important to know the ratio of these doses so that dosimeter readings may be properly interpreted.

Table 4.3 gives the measured dose-rate coefficients for TLDs on syringes. Positions A, B, C, and D correspond to those indicated in Figure 3.2. Position B is the point of maximum dose rate on the barrel at the middle of the solution volume, and position C is the point at which the syringes were held by the phantoms. For the gamma-emitters, dose-rate coefficients at position C are <6% of

those at position B, and dose-rate coefficients at position D are <2% of those at position B. For Y-90, dose-rate coefficients at position C are <2% of those at position B.

The ratios of TLD dose rates measured at position B in Figure 3.2 and the dose rates measured on the fingers are given in Tables 4.4 through 4.7. These ratios are the factors by which doses to dosimeters on specific fingers should be multiplied to obtain the maximum dose rate to TLDs on unprotected fingers holding a syringe at position B. The estimated dose-rate coefficients for dose to tissue averaged over 1 $cm^2$ depth can be obtained by additionally multiplying by the TLD to tissue correction factors given in Section 3.11 (2.1 for Y-90 and 1.2 for Tc-99m, I-131, and Lu-177). For example, the estimated dose-rate coefficient for dose to tissue averaged over 1 $cm^2$ at 7 mg $cm^{-2}$ depth for TLD ring dosimeters worn on the middle finger outside (MO), for 3-cc syringes containing 2.2 ml volume would be (3.95 x 100 x 2.1 =)829 Gy $s^{-1}$ $TBq^{-1}$ based on data in Table 4.4 and the 2.1 TLD to tissue correction factor.

These ratios range from 53 to 1,470 for Y-90, from 40 to 730 for Tc-99m, from 26 to 630 for I-131, and from 30 to 210 for Lu-177. The smallest ratios differ by no more than a factor of 2 for the different radionuclides. The smallest ratios were observed for dosimeters on middle fingers (the location closest to the radioactive material). The larger ratios vary by as much as a factor of 7.

**Table 4.3 Dose rates to TLDs as a function of location on syringes containing solutions of Y-90, Tc-99m, I-131, or Lu-177.**

| Radionuclide | Syringe size, cc | Volume in syringe, ml | Dose-rate coefficient[1], mGy $s^{-1}$ $TBq^{-1}$ | | | |
|---|---|---|---|---|---|---|
| | | | A[2] | B[3] | C[4] | D[5] |
| Y-90 | 3 | 2.2 | 4,650 | 3,950 | <6.3 | <6.3 |
| | 6 | 4.6 | 2,430 | 2,590 | <3.0 | <3.0 |
| | 12 | 8.6 | 995 | 1150 | <1.6 | <1.6 |
| Tc-99m | 3 | 2.0 | 54 | 60 | 1.0 | <0.4 |
| | 6 | 4.0 | * | 48 | * | * |
| | 12 | 8.0 | * | 43 | * | * |
| I-131 | 3 | 2.0 | 144 | 187 | 6.1 | <3.0 |
| | 6 | 4.0 | 104 | 136 | 5.0 | 1.6 |
| | 12 | 8.0 | 65 | 86 | 4.5 | 0.9 |
| Lu-177 | 3 | 2.0 | 20 | 21 | 0.6 | 0.3 |
| | 6 | 4.0 | 12 | 14 | 0.6 | 0.3 |
| | 12 | 8.0 | 7 | 9 | 0.5 | 0.1 |

1 Divide by 4.50 to obtain mrad $min^{-1}$ $mCi^{-1}$; activity is total activity in the syringe.
2 Location A is at the needle-end of the barrel.
3 Location B is centered on the volume.
4 Location C is at the finger end of the barrel.
5 Location D is at the thumb position on the plunger.
* Not measured.

**Table 4.4 Comparison of the TLD dose rates on syringes with the response of TLD ring dosimeters on phantoms holding different sizes of syringes containing different volumes of Y-90.**

| Syringe size, cc | Volume in syringe, ml | Surface TLD dose rate coefficient,[1] Gy $s^{-1}$ $TBq^{-1}$ | Relative dose rates [2] | | | | |
|---|---|---|---|---|---|---|---|
| | | | TP | IO | MO | RO | LO |
| 3 | 2.2 | 3.95 | 1,140 | 230 | 100 | 150 | 63 |
| 6 | 4.6 | 2.59 | 1,470 | 360 | 210 | 150 | 160 |
| 12 | 8.6 | 1.15 | 220 | 160 | 53 | 89 | 100 |

[1] Dose rate measured with a dosimeter on the surface of the syringe, centered over the volume. The volumes in the syringes on the phantoms were 2.2, 4.6, and 8.6 ml. Divide by 4.50 to obtain rad $min^{-1}$ $mCi^{-1}$.

[2] (surface dose rate) + (finger dosimeter dose rate), locations as indicated in Table 4.1.

**Table 4.5 Comparison of the TLD dose rates on syringes with the response of TLD ring dosimeters on phantoms holding different sizes of syringes containing different volumes of Tc-99m.**

| Syringe size, cc | Volume in syringe, ml | Surface TLD dose rate coefficient,[1] mGy $s^{-1}$ $TBq^{-1}$ | Relative dose rates [2] | | | | |
|---|---|---|---|---|---|---|---|
| | | | TP | IO | MO | RO | LO |
| 3 | 0.5 | 122 | >460 | >460 | 160 | 460 | >460 |
| | 1.0 | 95.9 | 730 | 100 | 56 | 150 | 460 |
| | 2.0 | 59.9 | 160 | 65 | 40 | 42 | 83 |
| 6 | 1.0 | 102 | 730 | 240 | 140 | 370 | 730 |
| | 2.0 | 74.3 | 170 | 120 | 64 | 150 | 200 |
| | 4.0 | 48.2 | 120 | 64 | 53 | 64 | 96 |
| 12 | 2.0 | 65.3 | 360 | 160 | 81 | 100 | 160 |
| | 4.0 | 49.5 | 160 | 79 | 52 | 79 | 160 |
| | 8.0 | 42.8 | 170 | 59 | 45 | 59 | 110 |

[1] Dose rate measured with a dosimeter on the surface of the syringe, and centered over the volume in the syringe. Divide by 4.50 to obtain mrad $min^{-1}$ $mCi^{-1}$.

[2] (surface dose rate) + (finger dosimeter dose rate), locations as indicated in Table 4.1.

**Table 4.6 Comparison of the TLD dose rates on syringes with the response of TLD ring dosimeters on phantoms holding different sizes of syringes containing different volumes of I-131.**

| Syringe size, cc | Volume in syringe, ml | Surface TLD dose rate coefficient, [1] mGy $s^{-1}$ $TBq^{-1}$ | Relative dose rates [2] | | | | |
|---|---|---|---|---|---|---|---|
| | | | TP | IO | MO | RO | LO |
| 3 | 0.5 | 473 | >630 | 160 | 160 | 160 | 630 |
| | 1.0 | 348 | 230 | 180 | 120 | 130 | 230 |
| | 2.0 | 187 | 120 | 61 | 49 | 51 | 81 |
| 6 | 1.0 | 221 | 290 | 140 | 71 | 110 | 290 |
| | 2.0 | 205 | 210 | 94 | 61 | 94 | 180 |
| | 4.0 | 136 | 130 | 66 | 48 | 53 | 77 |
| 12 | 2.0 | 154 | 140 | 87 | 57 | 87 | 120 |
| | 4.0 | 126 | 110 | 71 | 50 | 67 | 130 |
| | 8.0 | 86 | 96 | 40 | 26 | 36 | 62 |

[1] Dose rate measured with a dosimeter on the surface of the syringe, and centered over the volume in the syringe. Divide by 4.50 to obtain mrad $min^{-1}$ $mCi^{-1}$.

[2] (surface dose rate) + (finger dosimeter dose rate), locations as indicated in Table 4.1.

**Table 4.7 Comparison of the TLD dose rates on syringes with the response of TLD ring dosimeters on phantoms holding different sizes of syringes containing different volumes of Lu-177.**

| Syringe size, cc | Volume in Syringe, ml | Surface TLD dose rate co-efficient, [1] mGy $s^{-1}$ $TBq^{-1}$ | Relative dose rates [2] | | | | |
|---|---|---|---|---|---|---|---|
| | | | TP | IO | MO | RO | LO |
| 3 | 0.5 | 57.6 | 130 | 110 | 72 | 94 | 140 |
| | 1.0 | 37.2 | 160 | 110 | 92 | 110 | 210 |
| | 2.0 | 20.8 | 140 | 65 | 51 | 50 | 80 |
| 6 | 1.0 | 29.7 | 160 | 110 | 78 | 100 | 160 |
| | 2.0 | 22.9 | 170 | 87 | 60 | 83 | 110 |
| | 4.0 | 13.9 | 110 | 62 | 46 | 51 | 71 |
| 12 | 2.0 | 19.9 | 150 | 100 | 81 | 85 | 35 |
| | 4.0 | 14.4 | 120 | 86 | 49 | 74 | 120 |
| | 8.0 | 8.96 | 110 | 48 | 30 | 37 | 64 |

[1] Dose rate measured with a dosimeter on the surface of the syringe, and centered over the volume in the syringe. Divide by 4.50 to obtain mrad $min^{-1}$ $mCi^{-1}$.

[2] (surface dose rate) ÷ (finger dose rate), locations as indicated in Table 4.1.

## 4.7 HPGe Spectrometer Efficiencies

Figure 4.12 shows the results from nine independent efficiency calibrations of the HPGe spectrometer. The average efficiencies for the energies used in the calibrations, and their coefficients of variation are given in Table 3.1. No coefficient of variation was >4.2%. Hence, the uncertainty associated with the determination of activity of the solutions used for dosimetry was about the same as the uncertainty associated with the source used to calibrate the spectrometer (i.e., ±7%).

## 4.8 Y-90 Concentrations

The coefficient of variation for five different concentrations of Y-90 in the liquid scintillation counter was 1.3%. Multiple determinations of solution concentrations for all radioactive materials used in this work yielded coefficients of variation of <3% (i.e., within the uncertainty in pipetting).

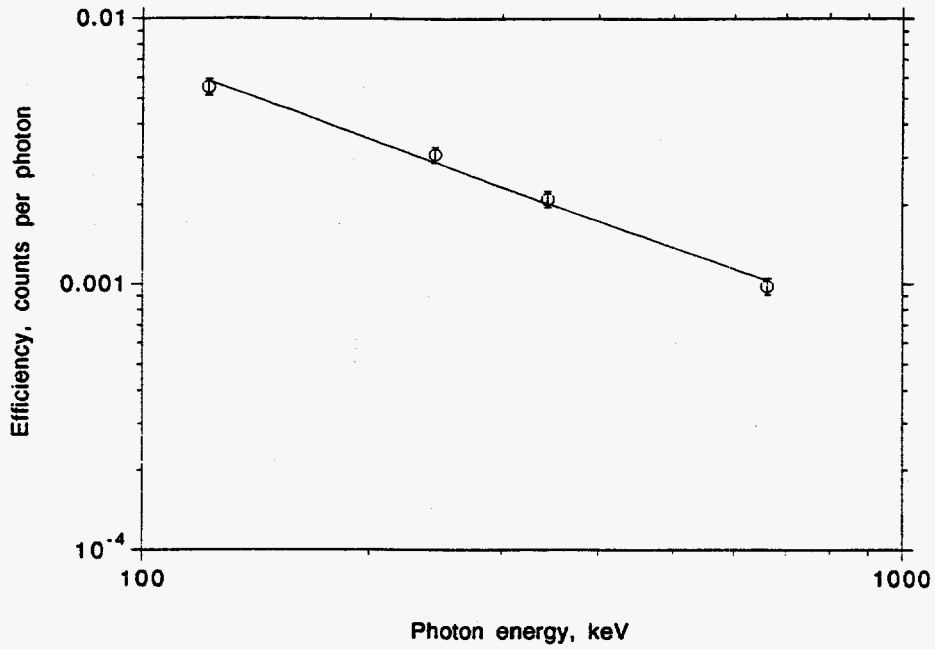


**Figure 4.12 Average efficiencies (with ± 7% error bars) as a function of photon energy for the HPGe spectrometer.**

## 4.9 Estimation of Dose to Skin in Contact with the Barrel of the Syringe

The dose to the skin at 7 mg $cm^{-2}$ depth was estimated using the results of TLD measurements and the correction factors described in Sections 3.11.1 and 3.11.2. The results are summarized in Table 4.8 for each isotope studied and 3-, 6-, and 12-cc syringes. Dose rates varied from 11 mGy $s^{-1}$ per TBq for Lu-177 to 8,295 mGy $s^{-1}$ per TBq for Y-90 (0.041 to 31 mrad $s^{-1}$ per mCi, respectively).

**Table 4.8 Estimated doses to tissue averaged over 1 $cm^2$ at 7 mg $cm^{-2}$ depth, based on TLD measured values adjusted to yield values in skin.**

| Radio-nuclide | Syringe size, cc | Solution volume, ml | Measured TLD dose rate coefficient mGy $s^{-1}$ $TBq^{-1}$ | Correction factor from Section 3.11 | Corrected tissue dose rate coefficient mGy $s^{-1}$ $TBq^{-1}$ | Corrected tissue dose rate coefficient mrad $s^{-1}$ $mCi^{-1}$ | Time to receive 0.5 Sv to skin for 3.7 x $10^8$ Bq (100 mCi) min |
|---|---|---|---|---|---|---|---|
| Y-90 | 3 | 2.2 | 3950 | 2.1 | 8295 | 31 | 0.27 |
| | 6 | 4.6 | 2590 | 2.1 | 5439 | 20 | 0.41 |
| | 12 | 8.6 | 1150 | 2.1 | 2415 | 8.9 | 0.93 |
| Tc-99m | 3 | 2.0 | 60 | 1.2 | 72 | 0.27 | 31 |
| | 6 | 4.0 | 48 | 1.2 | 58 | 0.21 | 39 |
| | 12 | 8.0 | 43 | 1.2 | 52 | 0.19 | 43 |
| I-131 | 3 | 2.0 | 21 | 1.2 | 224 | 0.83 | 10 |
| | 6 | 4.0 | 14 | 1.2 | 163 | 0.60 | 14 |
| | 12 | 8.0 | 9 | 1.2 | 103 | 0.38 | 22 |
| Lu-177 | 3 | 2.0 | 1.2 | 1.2 | 25 | 0.092 | 90 |
| | 6 | 4.0 | 1.2 | 1.2 | 17 | 0.063 | 132 |
| | 12 | 8.0 | 1.2 | 1.2 | 11 | 0.041 | 205 |

# 5 DISCUSSION

The results of this work apply only to the syringe sizes, volumes, and phantom geometries used. The geometry of the hand changes with the size of the syringe being used, and the volume it contains. In a dynamic model, the hand would close as the volume is delivered. Also, larger hands will involve greater distances between dosimeters on fingers and the radioactive content of a syringe. The mass of the hand will also affect the shielding of dosimeters by the fingers (especially for beta-emitters).

## 5.1 Dose Rates

Measurements of dose rates were made with dosimeters on the fingers of phantoms to determine the location for finger rings to be worn to best approximate the dose to the skin of the hand, and to determine correction factors to be applied to dosimeter measurements made on specific fingers.

Dose rates on the surfaces of syringes ranged from 11 mGy $s^{-1}$ $TBq^{-1}$ (2.5 mrad $min^{-1}$ $mCi^{-1}$) for Lu-177 to 8.3 Gy $s^{-1}$ $TBq^{-1}$ (1.9 rad $min^{-1}$ $mCi^{-1}$) for Y-90 where dose is averaged over 1 $cm^2$ at a depth of 7 mg $cm^{-2}$. The reader is cautioned that dose rates in practice will be the product of the amount of activity in a syringe and the dose rate per unit of activity in the syringe. The activity in 6 ml will be twice that in 3 ml given the same concentration of radioactive material in each. Hence, although the dose rate per unit of activity decreases with volume, the actual dose rate will increase with volume (given a constant concentration of radioactive material).

Dose-rate measurements on phantom hands, and corrections to estimate dose at 7 mg $cm^{-2}$ depth in skin were made without gloves on the hands. These dose rates would be lower by a few percent due to attenuation by the gloves normally worn by the technician or physician. However, the gloves of various thickness may be used at different installations. For gloves of known thickness, corrections to cited doses may be made using the attenuation curves shown in Figures 4.8, 4.9, 4.10, and 4.11 for Y-90, Tc-99m, I-131, and Lu-177, respectively.

## 5.2 Volume and Distance Considerations

The results of this work indicate that for a dose equivalent limit averaged over only 1 $cm^2$, dosimeters should be worn as close as possible to the radioactive materials in syringes. If a significant fraction of the expected dose may be due to skin contact with the syringe containing a RAB, only an estimate of the skin dose can be made from the dosimeter reading.

The ratios of maximum surface dose rates on syringes (position B, Figure 3.2) to dose rates measured by dosimeters on fingers of the phantom ranged from 53 to 1,500 for Y-90, 40 to 730 for Tc-99m, 26 to 630 for I-131, and 30 to 210 for Lu-177. The same ratios for dosimeters on the middle finger only were 53-210 for Y-90, 40-160 for Tc-99m, 26-160 for I-131, and 30 to 92 for Lu-177. As the volume of solution increased the range of these ratios decreased. For example, for dosimeters on the middle finger, given 8 ml in a 12-cc syringe, these factors range from 26 to 53 for all the radionuclides.

Dose rates to the fingers holding a syringe are best represented by dose rates at position C in Figure 3.2. Dose rates at position C are <2% of those at position B for Y-90, and <6% of those at position B for the other radionuclides (see Table 4.3). Hence, the ratios of dose rates on syringes at position C to dose rates measured on the middle finger of the phantom are 1 to 4 for Y-90, 2 to 10 for Tc-99m, 2 to 10 for I-131, and 2 to 6 for Lu-177. With two exceptions, 1 ml of Y-90 in a 6-cc syringe, and 1 ml of Lu-177 in a 3-cc syringe, the largest ratios are associated with the smallest volumes.

Keeping volumes large minimizes the dose rate per unit activity for small distances from

the source because the source is distributed with respect to the point of measurement. The observation that smaller syringes containing smaller volumes of radioactive materials produce higher dose rates than larger syringes containing larger volumes presents a dilemma for the practitioner because the larger the syringe, the less accurate the dosage unless large volumes are always delivered. Smaller syringes deliver greater accuracy in activity. However, they produce higher dose rates per unit activity to the handler. The higher the specific activity of the radioactive material, the more important this problem becomes. Also, problems with bubbles and pressure differentials between the vials and syringes are amplified with large syringes.

## 5.3 Techniques for Dose Reduction

To minimize the dose rate to the skin of the hand from a syringe containing gamma emitters, it is desirable to use oversized syringes for the volume to be administered so that the source is as far as possible from the fingers. For beta- and electron-emitters, it is better to fill the syringe with the maximum volume possible to create a distributed source and to optimize self absorption. The variables involved are syringe size, length and diameter of the radioactive solution in the syringe, and thickness and composition of the syringe's wall.

From the Y-90 results shown in Table 4.9 and 4.10, the largest doses occur from high-energy beta-particle emitters. It is suggested that shields be used on syringes when injecting RABs containing high-energy beta emitters; these consist of glass, plastic, or lead and are commercially available. However, lead is not recommended for Y-90 because of bremsstrahlung production.

An alternative to the syringe shield, which would also minimize photon dose, would be for the solution to be in a container which has an attached intravenous injection (IV) tube. This RAB solution can then be placed by the radiopharmacist in a shielded container (made of lead or thick plastic) with a hole for the IV tube to protrude through. The person administering the RAB would then only have to hang the shielded container and establish the IV.

The doses measured by the finger ring dosimeters will underestimate the dose to tissue directly on the syringe barrel if the finger dosimeter is at a relatively great distance (3-4 cm) from the barrel. Similarly, the beta dose may also be underestimated if workers wear it so that the finger is between the syringe source and the dosimetry media. For the fingers holding the syringe's barrel, the ring dosimeter's face should be toward the palmar side of the hand. For fingers on the hand used to push in the plunger, the ring dosimeter's face should be toward the back of the hand.

## 5.4 Uncertainties

Errors attributable to pipetting aliquots from stock solutions to vials for analysis by liquid or HPGe spectrometry are not greater than ± 2%. Inverse-square errors attributable to errors in positioning the TLDs around the Cs-137 source are not more than ± 7%. The uncertainty associated with the HPGe spectrometer is not more than ± 7%. The uncertainties associated with the liquid scintillation counting, and timing are not greater than ± 2%. The uncertainty associated with dosimeter readings is ± 5%.

The largest uncertainty related to filling syringes with different volumes is associated with a volume of 1.0 ml in a 6-cc syringe which can be read to within 0.1 ml. Hence, there is potential for as much as ± 10% uncertainty in the volumes contained in syringes. Uncertainties in positioning rings on phantoms and associated directional sensitivities of dosimeters are difficult to determine. However, the overall uncertainty associated with dose rates per unit activity in this report is estimated to be

not less than ±10% and not greater than ±15%.

The uncertainties in estimated dose at 7 mg $cm^{-2}$ tissue depth averaged over an area of 1 $cm^2$ for fingers on the barrel of the syringe from the photon component are estimated to be within ± 30%. The uncertainties for the beta dose component are estimated to be within ± 30%, since corrections have been made from measured values.

# 6 CONCLUSIONS

To minimize doses to the skin of the hand from occupational exposure, volumes of solutions and their distances from the skin should be maximized. That is, the specific activity of solutions should be minimized and the volume maximized. Unfortunately, this tends to conflict with efficient labeling of antibodies and other compounds. However, once antibodies are labeled, the concept can be applied to subsequent handling and administering of RABs.

Because RABs (especially when infused) are administered to patients in larger volumes than traditional radiopharmaceuticals, the dose rates per unit activity to handlers will be less than those from more conventional radiopharmaceuticals administered in small syringes.

Y-90 produces much higher dose rates than the other radionuclides used in this work. Beta-emitters produce higher surface dose rates per unit activity than gamma-emitters. However, with the exception of the high energy beta-emitters (e.g., Y-90), most of the beta particles are absorbed by the walls of syringes, infusion lines, and infusion reservoirs. So, although there is considerable risk of high beta doses to handlers of beta emitters, the risk can be reduced considerably by using plastic shielding, plastic gloves that are as thick as circumstances allow, and volumes of solutions that are as large as possible.

Dose rates on syringes from gamma-emitters can only be reduced a few percent by adding 3 mm of polypropylene to a syringe. The same thickness reduces the surface dose rate from Y-90 to less than one-tenth of its initial value.

Given the same amount of activity, Lu-177 presents no special dosimetric problems compared to the other radionuclides.

For the geometries used in these experiments, a dosimeter should be worn on the middle finger toward the outside of the hand that operates the syringe plunger to best estimate the maximum dose to the skin of unprotected fingers holding a syringe. Dose calculations for the other hand, that may be used to support the syringe, indicate that finger dosimeters should be worn on the inner (palm) side of the finger. The active volume should be kept as far as possible from the fingers consistent with handling dexterity. Filling a syringe to the point where a radioactive solution is between the fingers holding it should be avoided.

With the exception of Y-90, the highest dose rates measured on the phantom occurred on the middle finger. The difference between Y-90 and the other radionuclides is attributed to greater attenuation of the lower energy beta particles. For the radionuclides and geometries used in these experiments (i.e. using phantoms, not dosimeters in contact with the syringe), dose rates per unit activity measured by dosimeters on the outside of the middle finger will underestimate dose rates per unit activity to the skin of unprotected fingers by factors of 2 to 10, depending on the size of the syringe and the volume it contains. The thumb on the plunger of a syringe receives negligible dose compared to the fingers for all the radionuclides in these experiments.

Syringes are held in different ways in addition to the geometry used in this work. Another geometry that should be investigated is one in which the syringe is held in the palm of the hand and finger rings are worn on the palm-side of the fingers.

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# APPENDIX 1

## Major Instruments Used for Experimental Measurements of Dose and Activity

| Instrument | Description and comments |
|---|---|
| Analyzer amplifier | Canberra Industries, Inc. Mod. 3100-02, 4096 channels. |
| Barometer | Princo Instruments Inc., U.S. Signal Corps type (no model number). |
| Drying oven | Blue-M Electric Co., Mod. OV-8A, S.N. XAA-4433, used to anneal TLDs at 100°C before and after exposures. |
| Electrometer | Keithley, Mod. 617, (no S.N.), used to measure current or charge produced in the extrapolation chamber. |
| Electrometer | Keithley, Mod. 610B, used to monitor the bias voltage on the extrapolation chamber. |
| Extrapolation chamber | Nuclear Associates, Div. of Victoreen, Inc., PTW-Freiburg, NA 30-60, Type-Nr 23392-008, polyethylene terepthalate (Hostaphan® or Melinex®) window, perspex (Plexiglas®) collecting electrode, 3.003 cm collecting electrode diameter. |
| Furnace | Barber-Colman, Mod. 293, 0-1000 C, used to anneal TLDs at 400 C before exposures. |
| HPGe bias supply | Canberra Industries, Inc., Mod. 4261, 0-5 kV, S.N. 7811. |
| HPGe detector | EG & G ORTEC, GMX series, Model GNX-08180-S, 41.1 mm diameter x 40.4 mm long, 0.5 mm Be window, 3 mm endcap-to-crystal. S.N 24-N-42VB |
| Ion chamber rate meter | Eberline Instrument Corp, Mod. RO-2, S.N. 1798, 0.1-5000 mR/h. |
| Lab monitor | Eberline Instrument Corp. Radiation Monitor Mod. RM-14, S.N. 4566. |
| Liquid scintillation counter | Beckman LS 6000-IC, 20 ml UltamaGold (Packard Instrument Co., Inc.) cocktail in glass vials; used to calibrate Y-90 stock solution. |
| Multichannel analyzer | Canberra Industries, Inc., Series 35 Plus, Mod. 3502, with 3521 and 3575 options, S.N. 1085775. |
| Timer | SOURCECO Triple Digitimer, Mod. STD10, International Sourcing Corp. |
| TLD reader | Victoreen Mod. 2800-1G, S.N. 440. |

# APPENDIX 2

## Materials Used for Dosimetric Measurements

| Material | Description and comments |
|---|---|
| Am-241 + Eu-152+ Cs-137 | Amersham Corp., Am-241(10.2 kBq), Eu-152 (11.0 kBq), and Cs-137 (11.0 kBq), calibration date 1 Jun 1990, ± 7% overall uncertainty in activity, incorporated in solid plastic, 10 ml active volume in 20 ml glass vial, calibration traceable to NIST, used to calibrate the HPGe spectrometer |
| Cs-137 | 3 M Co., Mod. 6D6C-CA, S.N. 3M43-0001, 42.8 mCi ± 5% (5 Feb 1980), Cs-137 in microspheres, doubly encapsulated in stainless steel, 0.120" O.D. x 0.787" long, activity 0.0336" diameter x 0.464" long centered in the capsule, used to calibrate the extrapolation chamber and the TLD reader. |
| I-131 | Iodohippurate, Syncor Corporation, 74 MBq (2 mCi) supplied in a glass vial with septum, used for syringe dosimetry. |
| Lu-177 | Lutetium chloride in 0.2% HCL, Reactor Research Facility, University of Missouri, courtesy of Dow Chemical Co., 925 MBq (25 mCi) supplied in a plastic screw-cap bullet tube, used for syringe dosimetry. |
| P-32 | National Institute of Science and Technology (NIST) standard reference material, 7.4 MBq (0.2 mCi) ± 1%, in 5 ml of 0.01% ortho-phosphoric acid, supplied in a sealed glass ampule, used to confirm the efficiency of the liquid scintillation spectrometer. |
| Tc-199m | Pertechnetate, courtesy of the Division of Nuclear Medicine, University of Minnesota, 257 MBq (7 mCi) per experiment, supplied in a 1-cc syringe, used for syringe dosimetry. |
| Sr-Y-90 | Sealed source, RA-1 Medical Applicator, Tracerlab, Inc., approximately 74 MBq (2 mCi) in a glass matrix behind a thin aluminum window, used to calibrate the TLD reader for doses in TLDs from beta particles. |
| Y-90 | Yttrium chloride in 0.05N HCL, New England Nuclear 555 MBq (15 mCi) supplied in two NENSURE® vials with septa, used for syringe dosimetry. |
| Beta particle shield | Research Products International Corp., 0.5 " Lucite®. |
| Finger rings | Solon Technologies, Inc., for single TLD chips. |
| Impression material | The L. D. Caulk Div., Dentsply International Inc, Jeltrate®, alginate, Type II, regular set, used to make impressions of the investigator's hand to mold paraffin phantoms. |
| Lead shields | Custom made, 0.070" thick, and steel and lead bricks. |
| Paraffin | W & F Products, Inc., Paraseal® wax, used to make phantom hands. |
| Syringe holders & shields | Nuclear Associates, Div. of Victoreen, Inc., |

| | |
|---|---|
| Syringes | Monoject®, Div. of Sherwood Medical, polypropylene with rubber plunger-tip, Luer needle-tip, 3-cc (Mod. 513918, Lot No. 227151), 6-cc (Mod. 516911, Lot No. 340871), and 12-cc (Mod. 512910, Lot No. 720756), specific gravity 0.90 g $cm^{-3}$. |
| TLDs | STI/HARSHAW, Solon Technologies, Inc., LiF, TLD-100 ribbon, 1/8 x 1/8 x 0.035 in., Control numbers S3234 S(1) and S (2). |
| TLD annealing tray | Radiation Products Design, Inc., Part No. 163-000D, indexed, 1-100 cells. |
| Vials | Hollister-Stier, Div. of Miles Allergy Products, 30 ml, glass, sterile. |

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Exposure of the hands of medical personnel administering radiolabeled antibodies (RABs) was evaluated on the basis of (a) observing and photo-documenting administration techniques, and (b) experimental data on doses to thermoluminescent dosimeters (TLDs) on fingers of phantom hands holding syringes, and on syringes, with radionuclides in the syringes in each case. Dose rate coefficients to the skin, if in contact with the syringe wall, were 89, 1.9, 3.8, and 0.41 $\mu Sv\ s^{-1}$ averaged over 1 $cm^2$ at 7 mg $cm^{-2}$ per 37 MBq (1 mCi) for Y-90, Tc-99m, I-131, and Lu-177, respectively. When using Y-90 the importance of avoiding direct contact with syringes containing RABs and of using a beta-particle shield on the syringe was indicated. In using a syringe for injection, doses can best be approximated for the geometry studied by (a) wearing a finger dosimeter on the middle finger, toward the outside of the hand, on the hand operating the plunger, and (b) wearing finger dosimeters on the inner (palm) side of the finger on the hand that supports the syringe for energetic beta-particle emitters, such as Y-90 and Re-188.

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