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Less restrictive patient-specific radiation-safety precautions can be safely prescribed after permanent seed implantation

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Abstract

PURPOSE—To utilize radiation exposure-rate measurements to determine patient-specific radiation-safety instructions with the aim of reducing unnecessary precaution times and to evaluate potential doses to members of the public.

Materials and Methods—Radiation exposure-rate measurements were obtained from 1279 patients with stage T1-2 prostate cancer who underwent transperineal I-125 or Pd-103 seed implantation from January 1995 through July 2008. An algorithm was developed from these measurements to determine required precaution times needed to maintain public effective doses below 50% of the limits for specific exposure situations.

Results—The median air kerma rates at 30 cm from the anterior skin surface were 4.9 μ Gy/h (range: 0.1-31.5) for I-125 and 1.5 μ Gy/h (range: 0.02-14.9) for Pd-103. Derived algorithms depended primarily upon the half-life, T_p , the measured exposure rate at 30 cm, and specific exposure situation factors. For the typical Pd-103 patient, no radiation-safety precautions are required. For the typical I-125 patient, no precautions are required for co-workers, nonpregnant adults that do not sleep with the family member, or nonpregnant adults that sleep with the patient. Typical I-125 patients should only need to avoid sleeping in the “spoon” position (i.e., in contact) with pregnant adults and avoid holding a child for long periods of time in the lap for about 2 months.

Conclusions—The large number of cases available for this study permitted the development of an algorithm to simply determine patient-specific radiation-safety instructions. Resulting precaution times are significantly less restrictive than precaution times generally prescribed currently.

Keywords

Brachytherapy; Dose rate; Effective dose; Family members; I-125; Pd-103; Precautions; Prostate cancer; Public; Radiation safety; Seed

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Introduction

The use of I-125 for interstitial implantation was developed in the late 1960s and various sites of the body, including the prostate, were implanted with I-125 seeds starting in the 1970s (1). In the 1980s, revised implantation techniques based on the use of ultrasound resulted in a renaissance for the use of I-125 seeds in prostate implantation (2, 3). Around the same time, the use of Pd-103 seeds was also introduced as an alternate treatment modality. The popularity of seed implantation has continued to increase, as this technique has specific appeal to many patients. The number of procedures has grown from less than 5,000 in 1995 to between 40,000 and 60,000 in 2002 (4), which represents approximately 30%-40% of all eligible patients diagnosed annually in the United States (5). Prostate seed implantation is now considered a standard treatment intervention for localized prostate cancer, along with external beam radiotherapy and radical prostatectomy (6).

According to recommendations of the International Commission on Radiological Protection (ICRP), the National Council on Radiation Protection and Measurements (NCRP), and the guidance of the United States Nuclear Regulatory Commission (NRC), a medical facility may authorize the release from its control of any individual who has been administered byproduct material if the effective dose to any other individual from exposure to the released individual is not likely to exceed 5 mSv and the effective dose to a member of the general public is not likely to exceed 1 mSv (7-9). Because the total activity of I-125 or Pd-103 is typically greater than the 2 mCi or 8 mCi activity limits specified in the NRC guidance (8), prostate brachytherapy patients are to be given instructions on actions recommended to maintain doses to other individuals as low as reasonably achievable (ALARA).

The NRC does not require a specific set of patient instructions. Instead, instructions are left to the discretion of the facility. Radiation-safety precaution instructions to patients, therefore, have relied on a community consensus developed from literature and practice. These instructions are generally based on limiting time in the vicinity of the patient, particularly with regard to children and pregnant women (10, 11). Typical instructions have included not holding children in the patient's lap and not sleeping with a partner in the "spoon" position (i.e., with the partner in close contact with the anterior surface of the implanted patient) (11, 12). Typical instructions have been somewhat variably and generally set for 1-3 months for Pd-103 and 2-6 months for I-125 (11, 13).

There have been some peer-reviewed publications with data regarding measured dose rates or the variability of dose rates among patients following prostate brachytherapy (11, 14-17). The purpose of this study was to expand and update our earlier results as well as to utilize the large patient data set available at Memorial Sloan-Kettering Cancer Center (MSKCC) to broaden our knowledge of exposure and risk. In addition, our aim was to utilize this information to develop an algorithm employing exposure-rate measurements following implantation to determine patient-specific radiation-safety instructions with the aim of reducing unnecessary precaution times and evaluating the potential radiation doses to members of the public after I-125 or Pd-103 prostate seed implantation.

Materials and Methods

Study Population

Twelve-hundred seventy-nine (1279) patients with stage T1-2 prostate cancer who underwent transperineal implantation at MSKCC from January 1995 through July 2008 were studied. Of this group, 1127 cases utilized I-125 seeds and 152 cases utilized Pd-103 seeds in techniques previously described (2, 3). An Institutional Review Board waiver was obtained for retrieving and utilizing patient data.

Physical Measurements

Measurements of the amount of photon radiation emitted from patients are generally made with instruments that are calibrated to indicate exposure (X) in roentgens (R) or milli-roentgens (mR). Such measurements are simple to obtain and are taken at a point in a radiation field at specified distances from a patient. Exposure is generally defined as the total charge of the ions of one sign (typically negatively charged electrons) produced in a mass of air (18). It is related to the physical quantity air kerma (K_a), which is defined for this study as the sum of initial kinetic energies of all the charged ionizing particles liberated by photons in a mass of air (18). The relationship between the quantities K_a and X for photons emitted from treated patients at energies applicable to this study is as follows (19):

$$\dot{K}_a = 0.00876 \dot{X} \quad \text{Equation 1}$$

where K_a rate can be expressed as mGy/h and X rate in mR/h. In this study, radiation exposure-rate measurements were obtained in the immediate post-operative period (i.e., within 1-2 h) at the surface of the anterior skin at the point of the symphysis pubis. In a subset of patients (1018 cases), radiation exposure-rate measurements were also taken at 30 cm perpendicular from the surface of the anterior skin (approximating a 'lap' area exposure rate). Exposure-rate measurements were obtained using one of the following appropriately calibrated survey meters: a Keithley model 36100 radiation ionization chamber survey meter (Keithley Instruments, OH), a Fluke model 451B ion chamber survey meter (Fluke Biomedical, OH), or a microrem meter (Thermo Scientific, MA). These ion-chamber survey meters have a generally linear response through the I-125 and Pd-103 energy range. Calibration-corrected exposure readings for I-125 and Pd-103 energies were utilized in this study. All exposure-rate measurements were then converted to air kerma as indicated in Eq. (1) above prior to subsequent calculations.

The radionuclide utilized, either I-125 or Pd-103; the total activity (GBq) implanted; the measured exposure rate (mR/h); and the calculated air kerma rate ($\mu\text{Gy/h}$) were recorded and later evaluated retrospectively. In most cases, the exposure rates measured at a distance of 1 m were near the lower sensitivity of the measuring instruments. Therefore, exposure and air kerma rates at 1 m were conservatively calculated from the 30 cm reading using the point-source inverse square law geometry.

Radiation-Protection Quantities

The radiation-protection quantities utilized in this study are those recommended and defined in ICRP Publication 103 (9) and NCRP Report No. 82 (20), and by the NRC (21, 22). These quantities include the organ absorbed dose (D), organ equivalent dose (H_T), and effective dose (E). E is defined as the sum of the weighted equivalent doses to specific organs or tissues, H_T (i.e., each equivalent dose is weighted by a corresponding tissue weighting factor for the organ or tissue). These weighting factors for a particular organ or tissue represent the fractions of detriment (viz., from cancer and hereditary effects) attributed to that organ or tissue when the whole body is irradiated uniformly. Based on the radiation risks determined from epidemiological and animal studies, values of E are assigned as various effective dose limits (E_{limit}) for purposes of radiation protection (7).

With the development of advanced calculational techniques and models for the interactions of radiations with body organs (such as Monte-Carlo radiation transport analysis), it is possible to estimate directly the relationship between air kerma and effective dose using conversion coefficients published by the International Committee on Radiation Units (ICRU) (18) and the ICRP (23). In this study, the exposure geometries that typically apply to individuals exposed to prostate-implant patients include the anterior-posterior (AP) and

rotational geometries, as represented graphically in Fig. 1. Values for energy and yield-weighted E/K_a conversion factors were calculated for this study based on the American Association of Physicists in Medicine (AAPM) and ICRP recommended nuclear data for I-125 and Pd-103 for brachytherapy dosimetry (24, 25); these values are listed in Table 1.

The practical requirement for protecting a person from the radiation emitted by a patient is the determination of the effective dose, as discussed above, during the period of time when the exposure rate from the patient is significant. The effective dose is the product of the effective dose rate and the period of exposure. Because the exposure rate from the patient is continuously decreasing with time due to radioactive decay, the effective dose rate is also continuously decreasing and appropriate mathematical decay calculations are required to estimate effective doses to those exposed by the patient.

Two other interrelated parameters important in the estimation of effective dose are the occupancy factor and the index distance (7, 8). The occupancy factor, T_r , at an index distance, r , from a radioactive patient is the fraction of time an individual spends at that distance from the patient such that the sum of T_r over all index distances is equal to 1. For everyday activities, the NCRP notes that the index distance is set at 1 m and that the mean index distance between sleeping partners and between a child and an individual holding the child is set at 0.3 m (7). The occupancy factors, index distances, and effective dose limits utilized in this study are listed in Table 2.

When these radiation-protection parameters are combined mathematically, the effective dose to total decay at various distances from the patient can be calculated for therapeutic implants for which the time-dependent total-body activity follows a mono-exponential function (as is the case for sealed therapeutic seed implants that decay only by physical decay) using the following equation (8):

$$E_{(\infty)} = 34.56 T_r T_p (0.00876) \dot{X}_{(r,0)} (E/K_a)_r \quad \text{Equation 2}$$

where E = effective dose (mSv); 34.56 = conversion factor of integration equal to 1.44×24 (h/d); r = index distance (m); T_r = occupancy factor at index distance, r ; T_p = physical half life of the implanted radionuclide (d); $\dot{X}_{(r,0)}$ = initial calibration-corrected exposure rate at distance r (mR/h); and $(E/K_a)_r$ = effective dose per unit air kerma conversion factor for index distance, r , based on the exposure situation (mSv/mGy).

The total dose, $E_{(t \rightarrow \infty)}$ from a given exposure situation, if a patient maintains precautions for a time period, t (d), is then calculated using the following equation (7, 8):

$$E_{(t \rightarrow \infty)} = 34.56 T_r T_p (0.00876) \dot{X}_{(r,0)} (E/K_a)_r e^{\left(\frac{-0.693t}{T_p}\right)} \quad \text{Equation 3}$$

Table 2 includes the practical exposure situations and exposure geometries considered appropriate for those exposed to radioactive prostate seed patients. For those cases where an individual might be subject to more than one exposure situation (e.g., a child that lives in the same house as a patient and is held intermittently by the patient), the sum of each situation's contribution must be evaluated against the appropriate limit, E_{limit} , for that situation. For this study, five specific situations were considered when determining radiation-safety precautions: an adult family member that lives with but does not sleep with the patient, a nonpregnant adult family member that lives and sleeps with the patient, a pregnant family member that lives and sleeps with the patient, a child who is a family member that lives with and is periodically held by the patient, or a co-worker that does not live or sleep with the patient.

Algorithm Development

To develop a simple algorithm to calculate required precaution times for various exposure situations, and to ensure that effective doses are kept conservatively as low as reasonably achievable (ALARA), the total precaution times necessary to ensure that individuals are exposed to less than 50% of the applicable E_{limit} were iteratively calculated for the range of all possible exposure-rate measurements (mR/h) identified in our study population. The plot of exposure-rate readings (mR/h) versus precaution times for various exposure situations were mathematically fit to logarithmic best-fit equations. Thus, an individual can input directly the measured exposure-rate reading (mR/h) to calculate appropriate precaution times directly from exposure-rate readings without the need for unit conversions and iterative solutions. For exposure situations where the effective dose to total decay is less than 50% of the applicable E_{limit} e.g., $t=0$, there are no specific precautions required even at the highest measured exposure rates.

To verify the expected mono-exponential decay assumption, exposure-rate readings for a small subset of patients were taken at a clinical followup greater than 4 weeks post-implantation.

Results

The I-125 and Pd-103 data-collection and measurement results are summarized in Tables 3 and 4. The median air kerma rate at the anterior skin surface following an I-125 prostate implant was 22.8 $\mu\text{Gy/h}$ (range: 0.2-196). The median air kerma rate at 30 cm from the anterior skin surface (i.e., the “lap” area) following an I-125 prostate implant was 4.9 $\mu\text{Gy/h}$ (range: 0.1-31.5), resulting in a calculated air kerma rate at 100 cm from the anterior skin surface of 0.4 $\mu\text{Gy/h}$. Figs. 2 and 3 show the left-skewed variability in dose rate. At the anterior skin surface >90% of the measured values were $\leq 60 \mu\text{Gy/h}$ and at 30 cm >90% of the measured values were $\leq 10 \mu\text{Gy/h}$.

The median radiation air kerma rate at the anterior skin surface following a Pd-103 prostate implant was 7.1 $\mu\text{Gy/h}$ (range: 0.8-65.7). The median air kerma rate at 30 cm from the anterior skin surface (i.e., the “lap” area) following a Pd-103 prostate implant was 1.5 $\mu\text{Gy/h}$ (range: 0.02-14.9), resulting in a median calculated air kerma rate at 100 cm from the anterior skin surface of 0.2 $\mu\text{Gy/h}$. Figs. 4 and 5 show a left-skewed variability in air kerma rate similar to that seen for I-125. For air kerma rates at the anterior skin surface >85% of the values were $\leq 20 \mu\text{Sv/h}$ and for air kerma rates at 30 cm >90% of the values were $\leq 4 \mu\text{Sv/h}$.

Table 5 lists the results of sample calculations to determine the lifetime effective dose, $E(t)$, if precautions are followed for certain lengths of time (d) for various exposure situations. This table also compares these values against the conservatively chosen ALARA guideline of $0.5E_{limit}$ (mSv) for the individuals exposed. These sample calculations were performed using the median measured exposure rate of 0.5 mR/h at 30 cm from a patient that had received I-125 seeds to the prostate. As can be seen from the results in the table, no precautions are needed (i.e., the calculated lifetime effective dose is less than the ALARA guideline) in this example for co-workers, nonpregnant adult family members that do not sleep with the patient, or nonpregnant adult family members that sleep with the patient. Precautions are required for 82 d for pregnant adult family members that sleep with the patient and for 41 d for child family members that are held periodically by the patient because after these precaution times the calculated lifetime effective dose is less than the chosen ALARA guideline.

Calculations of this type were carried out iteratively for both I-125 and Pd-103 implants over the range of all possible exposure-rate measurements (mR/h) identified in our study population. For those cases that required precautions (i.e., when the calculated effective dose exceeds 50% of the effective dose limit for that exposure situation), a plot of exposure-rate readings (mR/h) at 30 cm from the anterior surface versus precaution times, $t(d)$, for various exposure situations were developed. Fig. 6 shows the calculation results for I-125 and indicates that the most restrictive precautions are required for pregnant adult family members that sleep with the patient. Fig. 7 shows the calculation results for Pd-103 and indicates that less restrictive precautions are required for these patients compared with those patients implanted with I-125. In addition, for Pd-103 no precautions are required for any exposure situations when the measured exposure rate at 30 cm from the anterior surface is less than 1.8 mR/h.

To simplify the determination of required precaution times, the results shown in Figs. 6 and 7 were mathematically fit to logarithmic best-fit equations in terms of the measured exposure rate at 30 cm from the anterior surface. The resulting best-fit equations each took on the following form:

$$t(d) = 1.44T_p \times \ln(\dot{X}_{30cm}) + f \quad \text{Equation 4}$$

This result is consistent with the expectation that precaution days depend primarily upon the half-life, T_p , of the radionuclide used for the implants; the measured exposure rate in the “lap” area at 30 cm, $\dot{X}_{30cm}$; and a factor, f , associated with the exposure situation being evaluated. These results take into account the conversion of exposure rate to effective dose rate as well as specifics of the exposure situation being evaluated (i.e., index distance, occupancy factor, and limit). Specific algorithms were then developed as tools to calculate appropriate precaution times directly from exposure-rate readings for various exposure situations for both I-125 and Pd-103. Table 6 lists each of the algorithms. Note that in exposure situations where the total lifetime effective dose is less than 50% of the applicable E_{limit} without any precaution times (i.e., when $t = 0$) even utilizing the highest measured exposure rates, no specific precautions are required to be given to the patient for that situation.

The expected mono-exponential decay assumption was verified by taking exposure-rate readings for a small subset of patients at a clinical followup >4 weeks post-implant. For I-125 implants, 20 patients were measured at an average of 38 days (range, 25-145) post-implant. Based on mono-exponential decay for I-125, the average fraction of initial exposure rate was expected to be 0.66 (range, 0.18-0.75) and the actual measured fraction of initial exposure rate was measured to be 0.64 (range, 0.18-0.77). For Pd-103 implants, 15 patients were measured at an average of 86 days (range, 40-110) post-implant. Based on mono-exponential decay for Pd-103, the average fraction of initial exposure rate was expected to be 0.05 (range, 0.01-0.2) and the actual measured fraction of initial exposure rate was measured to be 0.06 (range, 0.01-0.14).

Discussion

The study reported here is based on a large set of direct exposure-rate measurements taken immediately following implantation. Such a data set facilitates the useful evaluation of the variability of patient dose rates (Figs. 2, 3, 4, and 5), and provides a foundation for generic assumptions using median values, representing typical patients. The median effective dose rates following I-125 or Pd-103 permanent brachytherapy implantation are generally quite low. In all cases, effective dose rates calculated at 1 m were found to be less than the NRC

regulatory limits of 0.01 mSv/h for I-125 or 0.03 mSv/h for Pd-103(3, 8) that permit patient discharge from the hospital.

There is a marked variability in the air kerma rates from patient to patient (Figs. 2, 3, 4, and 5). This variability suggests that a patient-specific approach to identifying patient precautions as, developed in this study, is needed. The use of a direct exposure rate measurement on each patient in order to determine patient-specific precautions removes the effect of variability errors associated with general rules of thumb approaches. The wide range of reported rates is due in large part to the variability in total activity implanted and the variability in depth of the prostate. It has been shown previously that activity-normalized anterior surface effective dose rates ($\mu\text{Sv/h/GBq}$) generally decrease as patient weight increases, likely due to the fact that increasing patient weight generally increases the depth at which the prostate is located (11, 14). In addition, Cattani has clearly shown that the activity-normalized anterior surface dose rates are inversely correlated with distance between the implanted seeds and the skin surface (16). Thus, as theoretically expected, with more overlying tissue as de facto shielding, lower dose rates are expected for heavier patients.

This study extends and corroborates the findings of our earlier study (11). The results of median air kerma rates at the anterior skin surface were in agreement with those reported elsewhere (11, 14, 16, 17). Smathers et al (14) measured dose rates from 38 I-125 or Pd-103 prostate brachytherapy patients and suggested that patients need not be concerned about being a radiation risk to the general public following their procedures. Using optically stimulated dosimeters, Michalski et al (15) measured patient exposures and exposures to members of patient families from 44 patients receiving a permanent prostate brachytherapy implant (either with I-125 or Pd-103). These reports concluded that the exposure to family members from implanted patients was well below the NRC limits.

The lengths of time for patient precautions determined using direct exposure rate measurements and the conservative methodologies in this study are typically much less restrictive than the somewhat arbitrarily chosen lengths of time currently recommended (e.g., 1-3 months for Pd-103 and 2-6 months for I-125). Table 7 summarizes the precaution requirements over the range of measured exposure rates using simple algorithms prescribed in this study. No precautions are required for Pd-103 implants over the range of measured exposure rates in this study, even at the maximum exposure rate of 1.7 mR/h at 30 cm. No precautions are required for co-workers or nonpregnant adults that do not sleep with the implanted family member for I-125 implants over the range of measured exposure rates in this study. Similarly, no precautions are required for nonpregnant adults that sleep with the I-125 patient at the median exposure rate of 0.5 mR/h at 30 cm. At the median exposure rate, I-125 patients should avoid sleeping in the “spoon” position (i.e., in contact) with pregnant adults for 84 days and should avoid holding children in the lap for long periods of time (e.g., more than 1-3 hours) for 42 days. For the exceedingly rare occasion when the exposure rate measured from the patient is at the maximum exposure rate of 3.6 mR/h at 30 cm for I-125, patients should avoid sleeping in the “spoon” position (i.e., in contact) with nonpregnant adults for 115 days and should avoid sleeping in the “spoon” position with pregnant adults for 253 days. They should also avoid holding children in the lap for long periods of time for 211 days. However, for most patients, the precautions will be much less than this extreme case.

There are inherent limitations in any retrospective study associated with a selected patient population. Future prospective studies should evaluate the prostate depth using computed tomography images for our patient population, to enable a more rigorous evaluation of the thickness of overlying tissue. However, this study utilized patient-specific measured

exposure rates at 30 cm and such measurements inherently include any shielding provided by tissue.

Conclusion

This large data set provides a basis for the validation of current radiation-safety recommendations and provides clinicians with more concrete information regarding allowable exposure times for caregivers and members of the public after prostate implantation. Patients treated with either isotope I-125 or Pd-103 do not represent a radiation risk to members of the public (including children and pregnant women) when required radiation-safety instructions are observed and moderate exposure times are maintained.

A simple set of algorithms based on conservative assumptions has been derived for each exposure situation that allow calculations of the required precaution times needed to maintain effective doses to individuals potentially exposed to prostate implant patients below a conservatively chosen ALARA guideline of one-half of the associated effective dose limit. This study has identified that, for the typical Pd-103 patient, no precautions are required. For the typical I-125 implant patient, no precautions are required for co-workers, nonpregnant adults that do not sleep with the implanted family member, or nonpregnant adults that sleep with the patient. Most patients that receive I-125 implants should only need to avoid sleeping in the “spoon” position (i.e., in contact) with pregnant adults for about 2 months and to avoid holding children in the lap for long periods of time for about 1.5 months. These precautions are significantly less restrictive than currently suggested lengths of time.

References

1. Hilaris, B.; Holt, G.; St Germain, J. The use of iodine-125 for interstitial implants. DHEW publication 76-8022; Rockville, MD: 1975.
2. Holm HH, Juul N, Pedersen JF, et al. Transperineal ¹²⁵Iodine seed implantation in prostatic cancer guided by transrectal ultrasonography. *J Urol.* 1983; 130:283–286. [PubMed: 6876274]
3. Blasko J, Radge H, Schumacker D. Transperineal percutaneous iodine-125 implantation for prostatic carcinoma using transrectal ultrasound and template guidance. *Endocuriether Hyperthermia Oncol.* 1987; 3:131–139.
4. Grimm P, Sylvester J. Advances in brachytherapy. *Rev Urol.* 2004; 6(Suppl 4):S37–S48. [PubMed: 16985869]
5. Thomadsen BR, Williamson JF, Rivard MJ, et al. Anniversary paper: past and current issues, and trends in brachytherapy physics. *Med Phys.* 2008; 35:4708–4723. [PubMed: 18975716]
6. Stone NN, Stock RG. Permanent seed implantation for localized adenocarcinoma of the prostate. *Curr Urol Rep.* 2002; 3:201–206. [PubMed: 12084189]
7. NCRP. Management of radionuclide therapy patients. Bethesda, MD: National Council on Radiation Protection and Measurements. NCRP Report No. 155; 2006.
8. USNRC. Program specific guidance about medical use licenses. Vol. 9. Washington, DC: Division of Industrial and Medical Nuclear Safety. Office of Nuclear Material Safety and Safeguards. United States Nuclear Regulatory Commission; 2005. Consolidated guidance about materials licenses. Final report. Nureg-1556, rev 1
9. The 2007 Recommendations of the International Commission on Radiological Protection. ICRP publication 103. *Ann ICRP.* 2007; 37:1–332.
10. Anderson, L.; Nath, R.; Weaver, K. Interstitial collaborative working group. New York, NY: Raven Press; 1990. Interstitial brachytherapy, physical, biological, and clinical considerations.
11. Dauer LT, Zelefsky MJ, Horan C, et al. Assessment of radiation safety instructions to patients based on measured dose rates following prostate brachytherapy. *Brachytherapy.* 2004; 3:1–6. [PubMed: 15110306]

12. MSKCC. Patient education: Radioactive implants for the treatment of prostate cancer. Center MS-KC; New York, NY: 2008.
13. Ash D, Flynn A, Battermann J, et al. ESTRO/EAU/EORTC recommendations on permanent seed implantation for localized prostate cancer. *Radiother Oncol.* 2000; 57:315–321. [PubMed: 11104892]
14. Smathers S, Wallner K, Korssjoen T, et al. Radiation safety parameters following prostate brachytherapy. *Int J Radiat Oncol Biol Phys.* 1999; 45:397–399. [PubMed: 10487562]
15. Michalski J, Mutic S, Eichling J, et al. Radiation exposure to family and household members after prostate brachytherapy. *Int J Radiat Oncol Biol Phys.* 2003; 56:764–768. [PubMed: 12788183]
16. Cattani F, Vavassori A, Polo A, et al. Radiation exposure after permanent prostate brachytherapy. *Radiother Oncol.* 2006; 79:65–69. [PubMed: 16564593]
17. Anglesio S, Calamia E, Fiandra C, et al. Prostate brachytherapy with iodine-125 seeds: radiation protection issues. *Tumori.* 2005; 91:335–338. [PubMed: 16277100]
18. ICRU. Conversion coefficients for use in radiological protection against external radiation, ICRU report no 57. International Commission on Radiological Units and Measurements; 1998.
19. NIST. National Institute of Standards and Technology Report SP 250-58. Springfield, VA: National Technical Information Service; 2001. Calibration of x-ray and gamma-ray measuring instruments.
20. NCRP. SI units in radiation protection and measurements. Bethesda, MD: National Council on Radiation Protection and Measurements; 1985. NCRP report no 82
21. USNRC. Title 10 code of federal regulations, part 20. United States Nuclear Regulatory Commission; 1998. Standards for the protection against radiation.
22. USNRC. Title 10 code of federal regulations, part 35. United States Nuclear Regulatory Commission; 2008. Medical uses of byproduct material.
23. ICRP. Conversion coefficients for use in radiological protection against external radiation. ICRP publication 74. *Ann ICRP.* 1996; 26
24. Rivard MJ, Coursey BM, DeWerd LA, et al. Update of AAPM Task Group No. 43 Report: A revised AAPM protocol for brachytherapy dose calculations. *Med Phys.* 2004; 31:633–674. [PubMed: 15070264]
25. ICRP. Radiation safety aspects of brachytherapy for prostate cancer using permanently implanted sources. A report of ICRP publication 98. *Ann ICRP.* 2005; 35:iii–vi. 3–50. [PubMed: 16330284]

Glossary

AAPM	American Association of Physicists in Medicine
ALARA	as low as reasonably achievable
AP	anterior-posterior
<i>D</i>	organ absorbed dose
<i>E</i>	effective dose
<i>E_{limit}</i>	effective dose limits
<i>H_T</i>	organ equivalent dose
ICRP	International Commission on Radiological Protection
ICRU	International Committee on Radiation Units
ISO	isotropic
<i>K_a</i>	air kerma
LAT	lateral
MSKCC	Memorial Sloan-Kettering Cancer Center

NCRP	National Council on Radiation Protection and Measurements
NRC	Nuclear Regulatory Commission
PA	posterior-anterior
r	index distance
R	roentgens
ROT	rotational
T_r	occupancy factor
X	exposure

Fig. 1. Irradiation geometries of an anthropomorphic phantom showing antero-posterior (AP), postero-anterior (PA), lateral (LAT), rotational (ROT), and isotropic (ISO) geometry.

Fig. 2.
Values for anterior surface air kerma rate measured on contact of 1127 I-125 seed patients.
90% of values are $\leq 60 \mu\text{Gy/h}$.

Fig. 3.
Values for anterior air kerma rate measured at 30 cm from 921 I-125 seed patients. 90% of values are $\leq 10 \mu\text{Gy/h}$.

Fig. 4.
Values for anterior surface air kerma rate measured on contact of 152 Pd-103 seed patients.
85% of values are $\leq 20 \mu\text{Gy/h}$.

Fig. 5. Values for anterior air kerma rate measured at 30 cm from ^{97}Pd -103 seed patients. 90% of values are less than or equal to $4 \mu\text{Gy/h}$.

Fig. 6. Precaution days required for nonpregnant adult family members that sleep with the patient (solid curve), child family members periodically held by the patient (dashed curve), and pregnant family members that sleep with the patient (dotted curve) based on measured exposure rate at 30 cm for I-125 prostate seed implant patients.

Fig. 7.

Precaution days required for child family members periodically held by the patient (dashed curve), and pregnant family members that sleep with the patient (dotted curve) based on measured exposure rate at 30 cm for Pd-103 prostate seed implant patients.

Table 1

Nuclear data for I-125 and Pd-103 for brachytherapy dosimetry and weighted ratios of effective dose to air kerma

Radionuclide	Half Life [*] (d)	Photon Energy [*] (keV)	Photons per Disintegration [*]	Weighted Mean Energy (keV)	Weighted ROT [†] E/K _a (mSv/mGy)	Weighted AP [‡] E/K _a (mSv/mGy)
I-125	59.40	27.202	0.406	28.37	0.155	0.432
		27.472	0.757			
		30.98	0.202			
		31.17	0.0439			
		35.492	0.0668			
Pd-103	16.99	20.074	0.224	20.74	0.051	0.158
		20.216	0.423			
		22.72	0.104			
		23.18	0.0194			
		39.75	0.00068			
		294.98	0.00003			
		357.5	0.00022			
		497.1	0.00004			

^{*} Nuclear data from AAPM Report No. 84 (24) and ICRP Report No. 98 (25).

[†] ROT = rotational irradiation geometry (see Fig. 1) as interpolated from data in ICRU Report No. 57 (18).

[‡] AP = antero-posterior irradiation geometry (see Fig. 1) as interpolated from data in ICRU Report No. 57 (18).

Table 2

Occupancy factors, index distances, and effective dose limits*

Exposure Scenario Group/Activity	Occupancy Factors, T_r	Index Distances, r (m)	Effective Dose Limits, E_{limit} (mSv)
Family: nonsleeping partner/adult	0.25	1.0	5
Family: nonpregnant sleeping partner	0.33	0.3	5
Family: pregnant sleeping partner	0.33	0.3	1
Family: children or pregnant woman	0.25	1.0	1
Family: child held by patient	0.20	0.3	1
Public: co-worker	0.33	1.0	1

* As recommended by NCRP-155 (7).

Table 3

Summary of measured values for I-125 prostate seed implants

Description	Sample Size	Mean (s.d.)	Median	Minimum	Maximum
Total activity implanted (GBq)	1121	1.26 (0.39)	1.21	0.28	2.67
Surface anterior exposure rate (mR/h)	1127	3.39 (2.82)	2.6	0.02	22.4
Surface anterior air kerma rate ($\mu\text{Gy/h}$)	1127	29.7 (24.7)	22.8	0.18	196
Activity normalized surface anterior air kerma rate ($\mu\text{Gy/h/GBq}$)	1121	23.8 (17.9)	19.7	0.17	149
30 cm anterior lap exposure rate (mR/h)	921	0.57 (0.47)	0.50	0.01	3.6
30 cm anterior lap air kerma rate ($\mu\text{Gy/h}$)	921	4.97 (4.03)	4.90	0.07	31.5
Activity normalized 30 cm anterior lap air kerma rate ($\mu\text{Gy/h/GBq}$)	916	4.19 (3.40)	3.45	0.08	34.7

Table 4

Summary of measured values for Pd-103 prostate seed implants

Description	Sample Size	Mean (s.d.)	Median	Minimum	Maximum
Total activity implanted (GBq)	152	4.64 (2.01)	4.34	1.14	11.9
Surface anterior exposure rate (mR/h)	152	1.2 (1.2)	0.8	0.1	7.5
Surface anterior air kerma rate (μ Gy/h)	152	10.4 (10.4)	7.1	0.8	65.7
Activity normalized surface anterior air kerma rate (μ Gy/h/GBq)	152	2.30 (2.2)	1.6	0.1	22.2
30 cm anterior lap exposure rate (mR/h)	97	0.24 (0.24)	0.17	0.002	1.7
30 cm anterior lap air kerma rate (μ Gy/h)	97	2.10 (2.1)	1.46	0.02	14.9
Activity normalized 30 cm anterior lap air kerma rate (μ Gy/h/GBq)	97	0.40 (0.40)	0.30	0.01	2.79

Table 5

Sample results for typical exposure situations for I-125 prostate implants using the median measured exposure rate of 0.5 mR/h at 30 cm from a patient (bolded results represent those results that exceed the chosen ALARA guideline of $0.5E_{limit}$)

Exposure Scenario =		Co-worker		Nonpregnant Adult Nonsleeping		Nonpregnant Adult and Sleeping		Pregnant Adult and Sleeping		Child in House and Held	
Chosen ALARA Guideline (mSv) = $0.5E_{limit}$		$E(t_{-})$ (mSv)		$E(t_{-})$ (mSv)		$E(t_{-})$ (mSv)		$E(t_{-})$ (mSv)		$E(t_{-})$ (mSv)	
Precaution Time, t (d)											
0		0.041		0.031		1.313		1.313		0.808	
10		0.037		0.028		1.169		1.169		0.719	
20		0.033		0.025		1.040		1.040		0.640	
30		0.029		0.022		0.925		0.925		0.570	
40		0.026		0.020		0.823		0.823		0.507	
41		0.026		0.019		0.814		0.814		0.501	
42		0.025		0.019		0.804		0.804		0.495	
50		0.023		0.017		0.733		0.733		0.451	
60		0.021		0.016		0.652		0.652		0.401	
70		0.018		0.014		0.580		0.580		0.357	
80		0.016		0.012		0.516		0.516		0.318	
82		0.016		0.012		0.504		0.504		0.310	
83		0.016		0.012		0.499		0.499		0.307	
85		0.015		0.012		0.487		0.487		0.300	

* Values calculated for $E(t_{-})$ assume exposure continues over the full physical lifetime of the radionuclide after the precaution days.

Algorithms for determining the suggested precaution time, $t(d)$, for each exposure situation to maintain effective doses below the chosen ALARA guideline of $0.5E_{limit}$ based on measured exposure rate, $X_{30cm}(mR/h)$, at 30 cm from prostate implant patients. Note that if the calculated precaution time, $t(d)$, is 0, no precautions are required

Table 6

Exposure Scenario	I-125		Pd-103	
	Precaution Time, t(d)	Precaution Time, t(d)	Precaution Time, t(d)	Precaution Time, t(d)
Co-worker	0		0	
Nonpregnant adult not sleeping with implanted patient				0
Nonpregnant adult and sleeping with implanted patient	$85.54 \times \ln(X_{30cm}) + 5$		$24.47 \times \ln(X_{30cm}) - 53$	
Pregnant adult and sleeping with implanted patient	$85.54 \times \ln(X_{30cm}) + 143$		$24.47 \times \ln(X_{30cm}) - 14$	
Child in house and held periodically	$85.54 \times \ln(X_{30cm}) + 101$		$24.47 \times \ln(X_{30cm}) - 26$	

Algorithm-calculated required precaution times, $t(d)$, for each exposure situation to maintain effective doses below the chosen ALARA guideline of $0.5E_{limit}$ based on minimum, median, or maximum measured exposure rate, $X_{30cm}(mR/h)$, at 30 cm from prostate implant patients.

Table 7

Exposure Scenario	X_{30cm} (mR/h) =	I-125			Pd-103			
		Minimum	0.01	Median 0.50	Maximum 3.6	Minimum 0.002	Median 0.17	Maximum 1.7
		Precaution times, $t(d)$			Median Precaution times, $t(d)$			
Co-worker		0	0	0	0	0	0	0
Nonpregnant adult not sleeping with implanted patient		0	0	0	0	0	0	0
Nonpregnant adult and sleeping with implanted patient		0	0	0	115	0	0	0
Pregnant adult and sleeping with implanted patient		0	84	253	0	0	0	0
Child in house and held periodically		0	42	211	0	0	0	0