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Dosimetric characterization of ^{142}Pr glass seeds for brachytherapy

Jae Won Jung*, Warren Daniel Reece

Department of Nuclear Engineering, Texas A&M University, College Station, TX 77843-3133, USA

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Abstract

A glass bead consisted of the β^--emitting ^{142}Pr is proposed for brachytherapy treatment of prostate cancer. Appropriate radionuclide and seed dimensions were selected and sample seeds were manufactured. For the quantitative dosimetric parameters, two-dimensional dose distributions were calculated using the MCNP5 Monte Carlo code and measured using radiochromic film. The computational results compared well with measurements. Dose at 0.6 cm from the seed center can exceed 130 Gy. The reference dose rate, radial dose function and the anisotropy function were derived.

Keywords: Brachytherapy; Dosimetry; ^{142}Pr; Seed; Prostate cancer

1. Introduction

Over the last two decades, worldwide interest in the treatment of prostate cancer continues to increase. Prostate cancer is the most common cancer, after skin cancer, and the second leading cause of cancer-related death in men in the United States. Between 1988 and 1992, prostate cancer incidence rates increased dramatically due to earlier diagnosis with prostate-specific antigen (PSA) blood testing after already increasing steadily from 1975 to 1988. In contrast, incidence rates for both lung and colorectal cancers in men have declined in recent years (American Cancer Society, 2006). Early stage prostate cancer should be treated effectively with recurrence-free survival as the goal. Even though it is a slow growing cancer, optimized treatments should be selected considering the quality of life after treatment. Several options for the treatment of prostate cancer exist such as radical prostatectomy, watchful waiting, or radiation treatment (external beam radiation therapy or prostate brachytherapy). Surgical removal of the prostate can cause side effects such as erectile dysfunction or urinary incontinence. Intensity modulated radiation therapy or three-dimensional conformal therapy can give at most 85–90 Gy to prostate, while brachytherapy can deliver about 150 Gy to it. Several biological factors such as the α/β ratio or biological effective dose have been extensively studied. The α/β ratio is used to quantify the fractionation sensitivity of a cell or organs (Thames et al., 1982). Considering the small α/β ratio reported in literature (King and Fowler, 2001), higher doses to the tumor are better. One study (Brenner and Hall, 1999) reported that external beam therapy with hypofractionation or high dose rate (HDR) brachytherapy are more effective in the viewpoint of tumor control and late sequelae for the treatment of prostate cancer. Dale (1996) suggested that even though the same amount of total dose is deposited to a tumor or normal tissue, the biological effective dose for each radionuclide can be different from the physically prescribed dose due to the tumor doubling time, initial dose rate, tissue repair constant, relative biological effectiveness or other biological factors. The dose delivery time is closely related to the half-life of radionuclide used in the brachytherapy seeds and the tumor growth rate should be considered.

The most promising treatment option is prostate brachytherapy, also known as radioactive seed implant. Prostate brachytherapy can be used effectively for early stage prostate cancers before metastasis. A cross-sectional survey conducted by Wei et al. (2002) showed that even though brachytherapy is known for low morbidity and high recurrence-free survival, the current method of

*Corresponding author. Tel.: +1 979 845 7551.
E-mail address: jjw@ne.tamu.edu (J.W. Jung).

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brachytherapy treatment of prostate cancer is not preferred in terms of quality of life issues. As reported by Wallner et al. (1995), the dose to the urethra and rectum walls from conventional brachytherapy could be more than 360 and 90 Gy, respectively. This undesirable dose to adjacent organs is not insignificant.

The conventional treatment method is to implant several tens of ^{125}I or ^{103}Pd seeds into the prostate. To insert seeds into the prostate, ultrasound-guided transperineal template implant procedures are used. Considering that the mean free paths of 22 and 28 keV photons are 1.6 and 2.6 cm, respectively, some seeds can contribute to significant doses to the urethra and rectum walls. Although low energy photon sources such as ^{125}I and ^{103}Pd have a long history, side effects such as pain or burning during urination, and damage to the rectum and bladder walls are common. To reduce the undesirable dose to adjacent organs, we propose using a β^- source for the brachytherapy treatment of prostate cancer.

While β^- sources such as ^{90}Y, ^{188}Re and ^{32}P have been used for cancer therapy, β^- sources have not been widely used for brachytherapy. Nevertheless β^- sources offer several advantages over photon sources. β^- sources have short range and are easily shielded, lowering the dose for the medical staff as well as the patient. In the case of prostate cancer, the β^- emitting radionuclides can give a lower dose to the rectum and urethra than low energy photons. Fig. 1a shows the comparisons of radial dose function, $g(r)$ of ^{125}I (Rivard, 2002) and ^{90}Sr/^{90}Y (Roa et al., 2002). The radial dose function for ^{125}I is flat to 2 cm and decreases gradually to 10% at 10 cm, while the radial dose function for ^{90}Sr/^{90}Y falls off to 1.8% at 0.8 cm.

Rare earth aluminosilicate (REAS) glasses have been used as radioactive material vehicles because they can contain large amounts of β^--emitting rare earth isotopes, e.g. ^{90}Y, ^{166}Ho, ^{153}Sm, ^{165}Dy, or ^{142}Pr from 25 to 70 wt% (White and Day, 1994). REAS glasses are chemically durable and biologically inert *in vivo*. REAS glasses exhibit no measurable weight loss (>0.1 mg) for up to 6 weeks in distilled water. REAS glasses can be easily prepared as seeds for *in vivo* use or as microspheres of controlled size. REAS glasses are harder than window glass or vitreous silica. The Vickers hardness of REAS glasses is 6–8 GPa, while those of window glass and vitreous silica are less than 6 GPa. An application of REAS glasses is the treatment of primary hepatocellular carcinoma (liver cancer) with radioactive (^{90}Y) yttria aluminosilicate (YAS) glass microspheres (TheraSphere^{TM}). YAS microspheres are injected into the liver via the hepatic artery to deliver a therapeutic dose of β^- radiation to tumors (Salem et al., 2002). ^{142}Pr REAS glass microspheres have been studied for the treatment for arteriovenous malformations and the effects of the arterial size and microsphere size to dose profiles were evaluated (Lee and Reece, 2005).

The AAPM TG has suggested some practical guidelines for clinical physicists. The updated AAPM TG-43 report (Rivard et al., 2004) recommended a dosimetry protocol for interstitial brachytherapy sources and proposed standardized dosimetry parameters such as air-kerma strength and dose-rate constant. TG-43 parameters are explicitly for low energy photon emitters such as ^{125}I and ^{103}Pd and β^--emitting sources were not included. TG-43 recommends at least one experiment measurement and one Monte Carlo determination should be required for the clinical application of the seed. The AAPM TG-60 report (Nath et al., 1999) addressed intravascular brachytherapy physics and included the recommendation of dosimetry of β^- emitters.

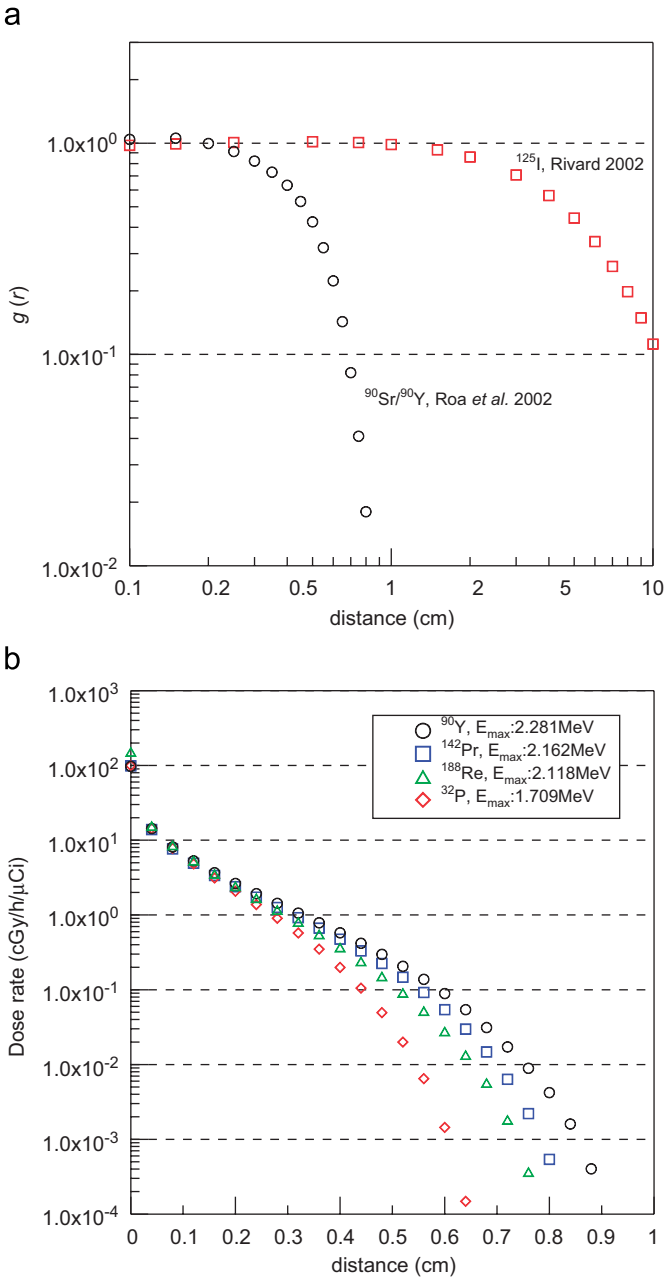

Fig. 1. (a) Radial dose functions of ^{90}Sr/^{90}Y and ^{125}I seeds. The radial dose function, $g(r)$ suggested in AAPM Task Group report no. 43 (TG-43) accounts for dose fall-off on the transverse-plane. (b) Radial dose profiles of several β^- emitters.

The present study developed a detailed brachytherapy scheme for prostate cancer using β^--emitting glass seeds. We selected an appropriate radionuclide and dimensions for brachytherapy seed and produced these brachytherapy seeds. After activating the seeds with neutrons, the dose distribution was determined both with Monte Carlo calculation and experimental measurements using radiochromic films to provide AAPM TG-43/60 dosimetric parameters. These seeds can be used not only for prostate brachytherapy treatment, but also for permanent breast seed implant as well as for head and neck cancers.

2. Methods and materials

2.1. Radionuclide selection and seed design

Although over 100 seeds are sometimes used to treat the prostate, 50 seeds were assumed for a typical implantation to lessen surgery time. If 50 seeds are used and the prostate is 50 g and 50 cm^3, one seed should cover 1 cm^3 of prostate volume and the target dose should be established at about 0.6 cm from seed's center. The target dose selected for this study is 150 Gy. This value is selected conservatively based on 144 Gy for ^{125}I and 125 Gy for ^{103}Pd. We seek to achieve this target dose using a radionuclide that produces high-energy β^- particles because we believe that adjacent tissues can be spared from unnecessary dose.

The seeds are activated in a thermal neutron flux density typical of research reactors so the neutron absorption cross-section should be large enough to make sufficient radioactivity easily in these neutron fields. As discussed earlier, a radionuclide with short half-life for HDR irradiation is acceptable. The seeds should have chemical, mechanical and biological integrity during neutron activation and *in vivo*. The cost of manufacture of these seeds should be relatively inexpensive. Finally, the seeds should be visible during surgery and post-implant monitoring with or without radiation opaque markers. The target activities can be easily controlled by knowing the neutron flux, activation time in the reactor and mass of target nuclide per seed.

To get the preliminary dose distribution, the BRAIN-DOSE code was used (Dauffy, 1998). BRAIN-DOSE code is based on SADDE (Reece et al., 1989) and VARSKIN (Traub et al., 1987) codes. BRAIN-DOSE integrates the Berger point kernels over the source volume, employing the scaled point kernels tabulated by Berger (1971). Dose point kernel (DPK) codes are fast and have good agreement in simple geometries when compared with Monte Carlo calculations. The Berger β^- DPK can be expressed as

$$B(\rho, E) = \frac{1}{4\pi\delta\rho^2}\int_0^{E_{\max}} \frac{EN(E)}{X_{90}} F\left(\frac{\rho}{X_{90}}, E\right) dE,$$

where ρ is the distance between the source point and the dose point (cm), δ the density of the irradiated medium (assumed to be unity for tissue) (g/cm^3), $N(E)$ the probability that a β^- particle is emitted with energy (MeV^{-1}), X_{90} the radius of the sphere within which 90% of the β^- energy is deposited from a point source in an infinite medium (cm) and F is the dimensionless scaled absorbed dose distribution as a function of ρ and the X_{90} distance.

For radionuclide selection, several possibilities were examined. Fig. 1b shows the radial dose profiles of various β^- emitters from BRAIN-DOSE code as a function of distance from the surface of the seed at the seed midpoint. The dose profiles are mainly dependent on the range of β^- particles. Yttrium and phosphorus have been used for intravascular brachytherapy. ^{90}Y glass microspheres have been used for hepatocellular carcinoma. However, ^{90}Y and ^{32}P have a small thermal neutron absorption cross-section. Re has large neutron cross-section but Re compound such as Re_2O_7 is not easy to incorporate into glass because of its volatility. Table 1 presents the comparison of the properties of several β^- emitters (KAERI, 2006).

Based on neutron activation analysis and BRAIN-DOSE calculations, ^{142}Pr was selected as the most appropriate radioisotope. Pr is a rare earth element suitable for REAS glass and ^{141}Pr has a sufficiently large cross-section for activation in small research reactors. Neutron activation of ^{141}Pr (100% natural abundance), results in production of both the 19.12-h ^{142}Pr ground state

Table 1
Properties of several β^- emitters

Property	^{142}Pr	^{90}Y	^{188}Re	^{186}Re	^{32}P
Half-life (h)	19.12	64.0	17.0	90.6	14.28 d
Maximum β^- energy (MeV)	2.162	2.281	2.118	1.071	1.709
Abundance of parent	1.000	1.000	0.626	0.374	1.000
Average energy (MeV)	0.809	0.934	0.765	0.323	0.695
Weight percent in glass	0.445[a]	0.4[b]	0.3[c]	0.3[c]	0.25[a]
γ-emissions for imaging	1.58 MeV, γ(3.7%)	Brems[d]	155.0 keV, γ(15%)	137.2 keV, γ(9.5%)	Brems[d]
Production cross-section of parent (thermal neutron)	7.5[b] (+3.9b)[e]	1.28[b]	73[b]	112[b]	0.17[b]

[a]MO-SCI Corporation (Rolla, MO 65402).
[b]Erbe and Day (1993).
[c]Conzone et al. (1998).
[d]Bremsstrahlung.
[e]Cross-section of meta-stable state.

and 14.6-m ^{142m}Pr meta-stable state with cross-sections of 7.5 and 3.9 b, respectively. ^{142m}Pr decays by 100% IT to ^{142}Pr. The ^{142}Pr decays by β^- emission with a 2.162 MeV endpoint energy at 96.3% of the time. The decay of ^{142}Pr is followed by emission of a 1.575 MeV γ-ray with 3.7% abundance (KAERI, 2006). With a 19.12-h half-life, 90% of the dose is deposited in 2.65 days.

2.2. Seed production

The Pr glass was manufactured by MO-SCI Corporation (Rolla, MO 65402). The seed diameter is 0.08 cm, the same as the typical ^{125}I seeds. Fig. 2a shows the seed dimensions and coordinate system based on AAPM TG-43. The length is twice that of the typical ^{125}I seeds to achieve the target dose at the edges of the field and to shorten surgery time. The density of Pr glass is 4.0 g/cm^3 and the weight percent of Pr is 44.5%. Table 2 presents the composition of Pr REAS glass.

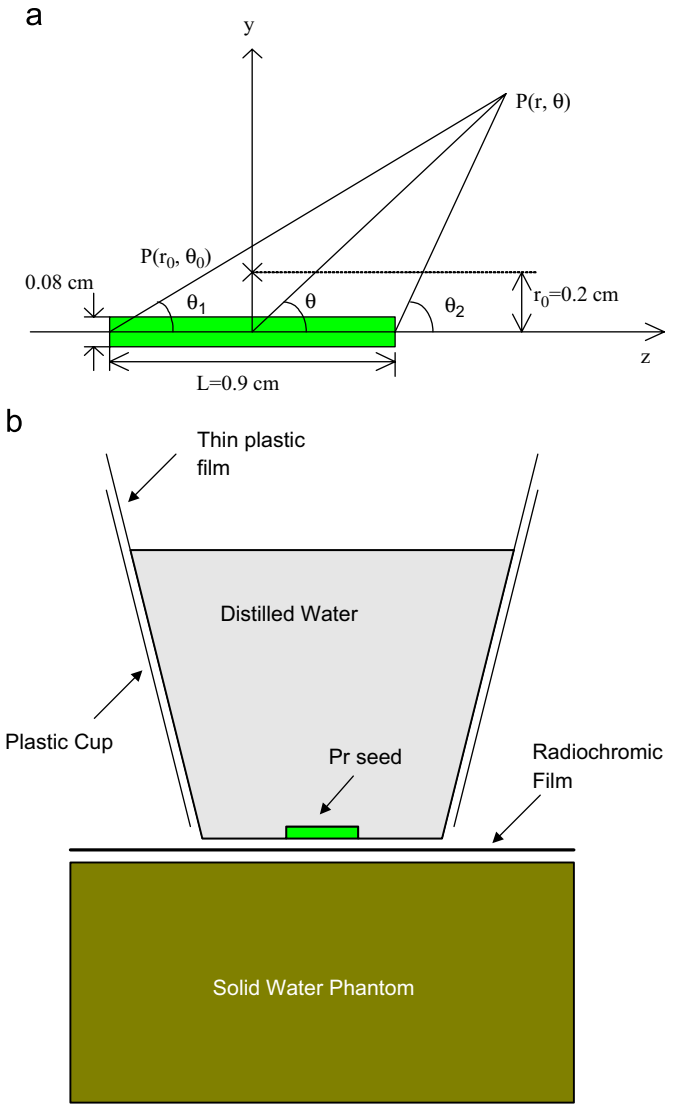

Fig. 2. (a) Seed dimensions and coordinate system; (b) experiment setup for two-dimensional dose distributions.

Table 2
Composition of Pr REAS glass seed

Element	Weight (%)	Mass in seed (mg)
Si	0.153	2.754
Al	0.081	1.458
Pr	0.445	8.010
O	0.321	5.778
Total	1.000	18.000

^{142}Pr REAS glass seeds have several advantages over conventional seeds. The Pr seed is economical; it costs $<$\$15 per seed including material and neutron activation costs. Due to the short range of β^- particles, the dose to adjacent organ can be minimized with the optimized implantation positions of the seeds. Because of the short half-life of ^{142}Pr, and associated HDR, distortion of the prostate during irradiation is less than with ^{125}I, for example, that emits 90% of its dose within 197.3 days. ^{142}Pr seeds may have application for other fast-growing cancers such as head and neck lesions. Pr seeds can have very high dose rates, if desired, and release kGy to the tumors adjacent to the seed. Because of high density and high atomic number of Pr glass, a radio-opaque marker is not necessary. Cladding or encapsulation is not required because the seed is unreactive in water or tissue. Variable sizes and shapes of glass seeds can be made and the seed is not easily broken. The seed can be used for an HDR treatment if a high neutron flux reactor having more than 10^{15} cm^{-2} s^{-1} is available. Within an hour, more than 145 Gy can be delivered at 0.6 cm from seed center with initial activity of 365 mCi. The seed is reusable after an HDR treatment by reactivation.

The Pr seeds were activated in the TRIGA reactor at the Nuclear Science Center at Texas A&M University. Si and Al, as well as Pr were activated in the reactor. However, ^{28}Al has only 2.24-min half-life and ^{31}Si has 2.62-h half-life with 0.07% yield of γ-rays. Cd-covered Au-foil and bare Au-foil were used to measure the neutron flux at the activation location. The activities of Au-foils were measured using a HPGe detector and the neutron flux of thermal and epi-thermal neutrons was estimated to be $(1.48 \pm 0.05) \times 10^{13}$ cm^{-2} s^{-1} and $(6.98 \pm 0.54) \times 10^{11}$ cm^{-2} s^{-1}, respectively. Based on the neutron flux measured with the gold foils, the activities of ^{142}Pr were calculated using neutron activation equations and measured with a HPGe detector.

After meta-stable decay, 36% of total radioactivity of ^{142}Pr was derived from the meta-stable state. After three half-lives of ^{142m}Pr, the total radioactivity is at maximum. Immediately after activation, the ^{142}Pr seed is too active to measure on the HPGe detector. The radioactivity was measured after several half-lives of ^{142}Pr, and then back extrapolated to the end of the neutron activation. The produced radioactivity was as expected considering meta-stable state and epi-thermal neutron flux.

2.3. Monte Carlo simulation

MCNP5 code was used to calculate the quantitative dosimetric parameters of the seeds. MCNP is a general-purpose Monte Carlo code. It can be used for neutron, photon, electron, or coupled neutron/photon/electron transport with the default modeling of secondary radiations such as positrons, K-edge characteristic X-rays and bremsstrahlung. It can model an arbitrary three-dimensional geometry and various source types such as point, volume and surface with user-defined source spectrum. A continuous-slowing-down model is used for electron transport (X-5 Monte Carlo Team, 2003).

The MCNP5 base model for the glass seed was developed. Dosimetry data in water were calculated at radial distances from the glass seed from 0.1 to 0.9 mm, and over angles ranging from 0° to 90° using *F8 tallies in 0.02-cm diameter water receptors. Dose can be calculated as *F8 tally divided by mass of detector cells. Mode P E was used with default modeling of bremsstrahlung. Mcplib04 and el03 cross-section libraries were used for the electron- and photon-coupled transport. A cylindrical volume source was modeled. The radioisotope was assumed to be uniformly distributed in the seed. Two major radiations were considered, 2.162 MeV endpoint energy β^- particles and 1.575 MeV γ-rays. An "ITS-style" energy-indexing algorithm (Jeraj et al., 1999) was used and the number of source electron histories was chosen so that there was less than 1% statistical error at the reference point.

2.4. Measurement

To verify the Monte Carlo calculation, the two-dimensional dose distribution was measured around the seed. Radiochromic dye films were used for measuring the spatial two-dimensional dose distributions mostly because of the short range of β^- particles. Radiochromic film is tissue-equivalent and its color is stable with time after development time of 24 h. GAFCHROMIC® MD-55-2 (Nuclear Associates) is doubly layered and water resistant except at the edge of the films (Butson et al., 2001).

The radiochromic films were calibrated using an X-ray machine (Norelco Model MG-300) at the Nuclear Science Center. The radiochromic films were exposed to known doses of X-rays calibrated against NIST traceable ion chamber and the calibration curve was derived and fitted based on the net optical density ($_{net}$OD) of known doses. The calibration curve can be used for the dose profile of 2 MeV β^- particles without correction. The color change of the films were read using an Epson Perfection 2480 PHOTO scanner and converted to 8 bit in MATLAB software. From these data, optical densities were generated and two-dimensional dose profiles were derived.

As shown in Fig. 2b, a Solid Water™ phantom (manufactured by Gammex®) was used to provide full backscattering conditions during measurements. The Solid Water™ phantom material is designed to have the same electron density as water. The radiochromic film was placed on the top of the solid water phantom. Distilled water inside a 14-μm thick plastic film (Reynolds®) was put in a plastic cup with the bottom removed. The thin plastic film prevented the distilled water from contacting the radiochromic film. The activated ^{142}Pr glass seed was placed in the middle of the bottom of a container of distilled water and the radiochromic film exposed for known times.

This study is designed for informational purposes only and the seed has not been tested on any animals or humans nor is it approved for clinical applications.

3. Results and discussion

3.1. Monte Carlo calculation

Fig. 3a shows radial dose profiles from DPK and MCNP5 calculations. The profiles have a good agreement up to 0.6 cm but beyond 0.6 cm, the DPK code underestimates the dose.

Fig. 3b shows the comparisons of radial dose profiles of various seeds. Even though the design and dimensions of the seeds are different, note that the dose profiles of ^{142}Pr are in a reasonable range compared with those of other β^--emitting seeds (Asenjo et al., 2002; Mourtada et al., 2004).

Fig. 3c shows the radial dose profiles of β^- and γ dose from Pr seeds. The dose profile from β^- decreases gradually to 0.6 cm because of the low-energy part of the spectrum of β^- particles and drops sharply after 0.6 cm (the range of average β^- energy). The dose profile is obviously also controlled by geometry effects. The dose profile of γ decreases gradually and the γ dose is dominant beyond 0.9 cm. Calculations suggest that the total dose in water at 1.0 cm from the source with initial activity of 6.56 mCi is 0.3 Gy which is insignificant to adjacent organs.

The total dose at $r = 0.6$ cm and $\theta = 90°$ was calculated to 130.8 Gy. Considering the other side of seed can give another same dose to a dose point, the dose at $r = 0.6$ cm and $\theta = 90°$ can be equal to 261.6 Gy. The results show that the seed can achieve the target dose and meet the seed design criteria.

3.2. Radiochromic film measurement

Radiochromic film was exposed 1 h post-irradiation for 19.12 h (one half-life of ^{142}Pr) which gave half the total dose. Fig. 4a shows the two-dimensional dose profiles from Monte Carlo simulation and film measurement. The interpolation was performed using the kriging algorithm in the SURFER® program. The calculated and measured dose distributions are in excellent agreement. The sensitivity of the radiochromic film is from 3 to 100 Gy, so the doses above 200 Gy are not shown for film measurement.

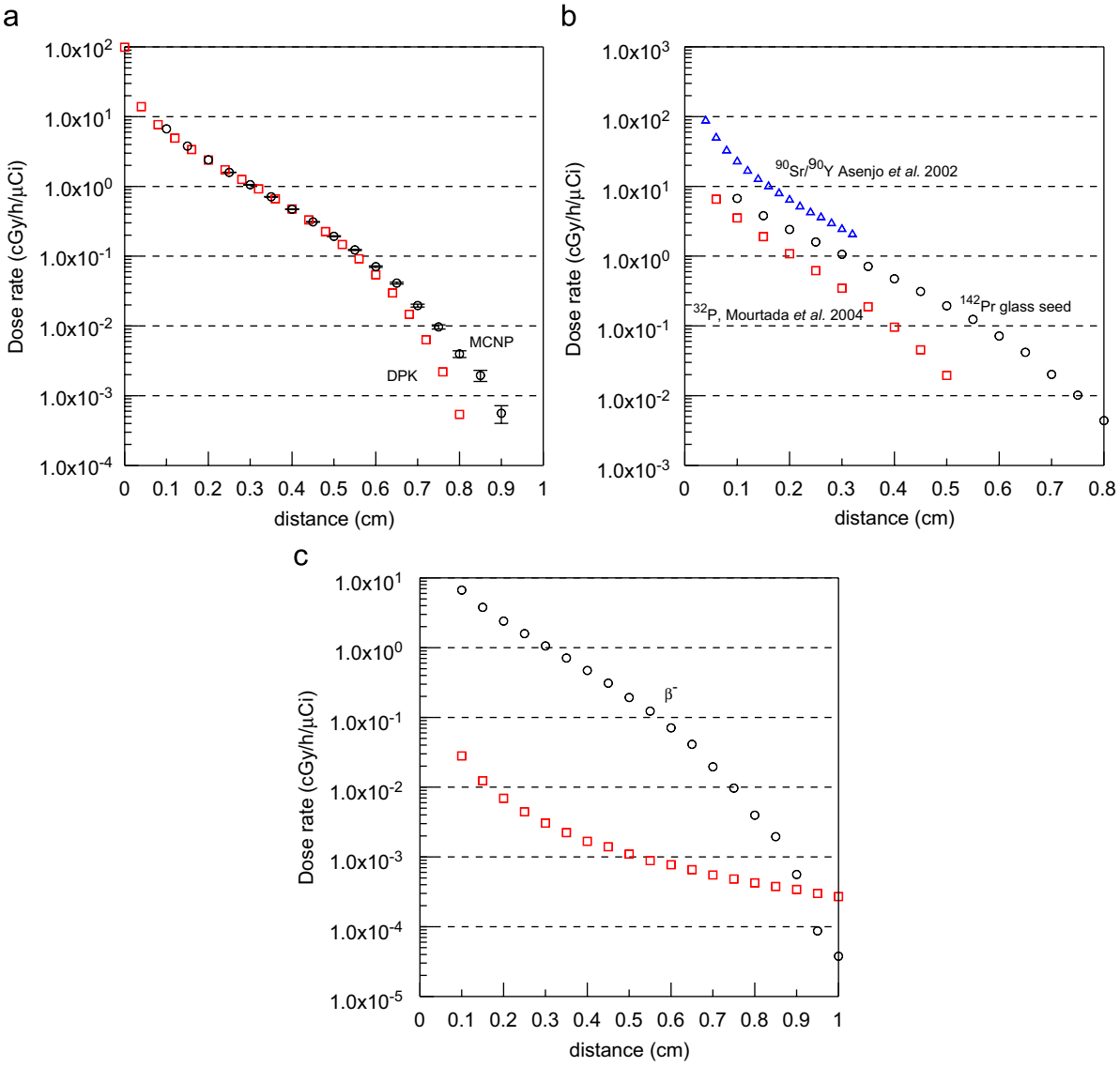

Fig. 3. (a) Radial dose profiles of DPK and MCNP5 calculation; (b) comparison of radial dose profiles of various β^- emitters and (c) radial dose profiles of β^- and γ dose from ^{142}Pr.

3.3. AAPM TG-60 parameters

The dosimetric parameters defined in AAPM TG-60/TG-43 were determined using the Monte Carlo calculations, including: reference dose rate, radial dose function and two-dimensional anisotropy function. The coordinate system can be seen in Fig. 2a. The dose at a point can be expressed as

$$D(r,\theta) = D(r_0,\theta_0)\left[\frac{G(r,\theta)}{G(r_0,\theta_0)}\right] g(r) \times F(r,\theta),$$

where r is the radial distance from the source, θ the angle between the line segment from point of interest to center of source, $G(r,\theta)$ the geometry function resulting from spatial distribution of the radioactivity within the source, $g(r)$ the radial dose function, $F(r,\theta)$ the two-dimensional anisotropy function describing the dose variation and $D(r_0,\theta_0)$ is the dose rate in water at the reference point. The reference point suggested in AAPM TG-60 is $r_0 = 0.2$ cm and $\theta_0 = 90^\circ$. The geometry function, $G(r,\theta)$ was derived using a simple line-source equation with $L = 0.9$ cm expressed as

$$G(r,\theta) = \frac{\theta_2 - \theta_1}{Lr\sin\theta},$$

where L is the length of seed containing radioactive components.

3.3.1. The reference dose rate for ^{142}Pr source

The reference dose rate was estimated 1 h after end of 1-h neutron activation. One-hour neutron activation in $1.5 \times 10^{13}\,\mathrm{cm^{-2}\,s^{-1}}$ can produce 5.5 mCi of ^{142}Pr. The dose rate at reference dose point $D(r_0,\theta_0)$ and a target point $D(r = 0.6\,\mathrm{cm},\theta_0)$ based on two-dimensional dose distributions in water is estimated to 2.412 ± 0.0099 and 0.072 ± 0.0017 cGy/h/μCi, respectively.

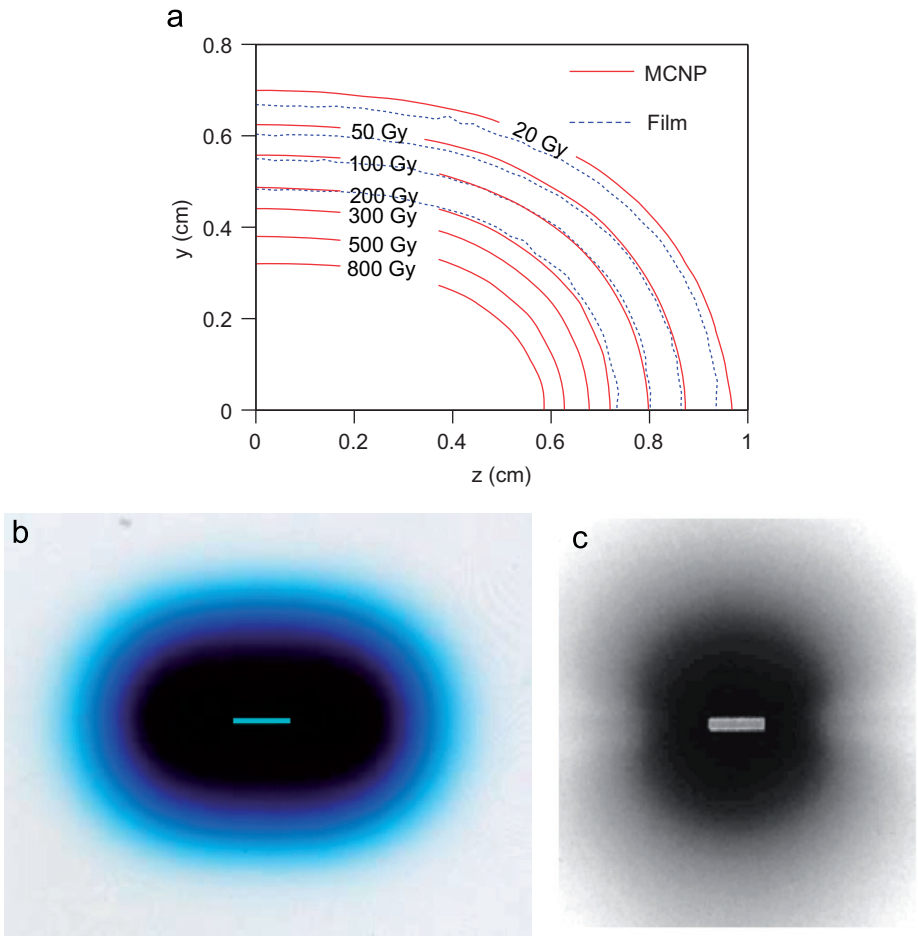

Fig. 4. (a) Comparison of isodose plots of Monte Carlo calculation (solid lines) and radiochromic film measurement (dotted lines); (b) radiochromic film image of ^{142}Pr seeds and (c) autoradiograph of ^{131}Cs seed, available at: ⟨http://www.isoray.com/assets/InvestorPresentation9606lw.pdf⟩ (''seed'' superimposed and scaled for illustration).

3.3.2. The radial dose function, g(r)

The radial dose function $g(r)$ is calculated as

$$g(r) = \left(\frac{D(r,\theta_0)}{D(r_0,\theta_0)}\right)\left(\frac{G(r_0,\theta_0)}{G(r,\theta_0)}\right).$$

The radial dose function can be expressed using a least-squares fit of a fourth-order polynomial as

$$g(r) = a_0 + a_1 r + a_2 r^2 + a_3 r^3 + a_4 r^4,$$
$$a_0 = 1.2370, \quad a_1 = 0.2378,$$
$$a_2 = -9.5302, \quad a_3 = 13.5450,$$
$$a_4 = -5.4887.$$

where r is the radial distance (in cm) from the source.

The radial dose function $g(r)$ fourth-order polynomial coefficients are valid from 0.1 to 0.9 cm. The coefficient of determination is 0.999.

3.3.3. The anisotropy function, F(r, θ)

The two-dimensional anisotropy function, $F(r,\theta)$, is defined as

$$F(r,\theta) = \left(\frac{D(r,\theta)}{D(r,\theta_0)}\right)\left(\frac{G(r,\theta_0)}{G(r,\theta)}\right).$$

The two-dimensional anisotropy function describes the variation of the dose rate around the seed, in the r distance and θ direction. Table 3 presents values of the two-dimensional anisotropy function. The maximum value of the anisotropy function was estimated as 32.9. This is because the isodose profile is elliptical as shown in Fig. 4b. Most conventional seeds have significant cold spots at the ends of the seed due to attenuation through the seed and encapsulation at the edges as shown in Fig. 4c, while the Pr seed has no cold spot as shown in Fig. 4b. Table 4 presents one-dimensional anisotropy function of ^{142}Pr glass seed. One-dimensional anisotropy function was derived based on the definition suggested by AAPM TG-43.

4. Conclusion

A β^--emitting glass seed is proposed for the brachytherapy treatment of prostate cancer. Seed design criteria were derived and several β^--emitting nuclides were examined for suitability. ^{142}Pr was selected as radioisotope of choice. Seeds, 0.08 cm in diameter and 0.9-cm long, were activated in a university research reactor and manufactured for

Table 3
Two-dimensional anisotropy function for the ^{142}Pr seed

θ (°)	r (cm)																
	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90
0									3.062	3.250	3.969	4.814	7.118	9.594	15.050	18.430	32.863
10					1.701	2.009	2.485	2.597	2.801	3.149	3.870	4.847	6.947	9.551	14.655	18.026	30.750
20		1.187	1.234	1.349	1.547	1.823	2.096	2.373	2.732	3.011	3.785	4.541	6.455	8.531	13.231	16.118	25.897
30	1.083	1.106	1.179	1.289	1.449	1.625	1.847	2.057	2.393	2.683	3.192	3.847	5.484	7.021	10.800	12.720	18.183
40	1.048	1.083	1.124	1.205	1.334	1.455	1.610	1.751	2.012	2.250	2.674	3.098	4.212	5.128	7.669	8.064	11.207
50	1.014	1.053	1.100	1.138	1.203	1.298	1.399	1.502	1.677	1.781	1.992	2.313	3.093	3.640	5.155	5.323	6.807
60	0.997	1.030	1.056	1.079	1.125	1.169	1.222	1.273	1.399	1.451	1.609	1.738	2.132	2.373	2.852	3.018	3.142
70	1.002	1.020	1.025	1.028	1.058	1.090	1.088	1.118	1.180	1.139	1.269	1.220	1.533	1.590	2.014	1.971	1.712
80	1.010	1.006	1.000	1.002	1.021	1.017	1.030	1.030	1.047	1.005	1.068	0.971	1.105	1.061	1.202	1.022	1.395
90	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Table 4
One-dimensional anisotropy function for the ^{142}Pr seed

r (cm)	^{142}Pr glass seed (MCNP)
0.50	2.552
0.55	2.447
0.60	2.729
0.65	2.917
0.70	3.882
0.75	4.340
0.80	7.289
0.85	6.762
0.90	16.944

testing. The radioactivity was as expected considering meta-stable state and epi-thermal neutron flux.

The MCNP5 Monte Carlo code was used to calculate the quantitative dosimetric parameters suggested in the AAPM TG-43/60 reports. The Monte Carlo calculation results were compared with those from a DPK code. The dose profiles have a good agreement with each other out to 0.6 cm within 4.2% difference. The total dose of ^{142}Pr was estimated to 0.3 ± 0.02 Gy at 1.0 cm with initial activity of 6.6 mCi from MCNP5 code calculation.

Measurements were performed to assess the two-dimensional axial dose distributions using radiochromic film. The radiochromic film was calibrated using an X-ray machine calibrated against a NIST-traceable ion chamber over the appropriate energy range. A calibration curve was derived using a least-squares fit of a second-order polynomial. The measured dose distribution agreed with results from Monte Carlo simulations. The dose at 0.6 cm from the seed center with initial activity of 6.6 mCi was 131 Gy. AAPM TG-43/60 brachytherapy dosimetry parameters were determined. The reference dose rate for 0.2 and 0.6 cm were 2.412 and 0.072 cGy/h/μCi, respectively. The radial dose function, two-dimensional anisotropy function and one-dimensional anisotropy function were generated.

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