Photon spectral characteristics of a new double-walled Iodine-125 source[a)]

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The photon spectral characteristics of a recently designed Iodine-125 source have been measured. The source has a physical length of 5 mm and a diameter of 0.8 mm. A thin tungsten filament coated with radioactive Iodine-125 is used as a radiographic marker and is encapsulated in a double wall titanium shell of uniform thickness all around. The photon spectral characteristics, measured with an intrinsic germanium (Ge) detector coupled to a multichannel analyzer, reveal that the seed emits the 27.4-keV K_α and 31.4-keV K_β x rays and 35.5-keV γ photons from the decay of Iodine-125. Because of their low energy, the tungsten x rays are not observed in the spectrum. The anisotropy of the radiation fluence for each of the above-mentioned photon energies was measured in planes containing the seed short and long axes. The 4π-averaged anisotropy factor for the total radiation fluence, i.e., sum of the above three photon energies is 0.92. The photon intensity radiated along the seed long axis is approximately equal to the intensity in the seed transverse direction due to the absence of end welds. The new Iodine-125 source is characterized by good radiographic visualization, greater structural strength due to double wall encapsulation design, and emission of more isotropic Iodine-125 photon spectrum.

Key words: Iodine-125 seed, dosimetry, brachytherapy, photon anisotropy

INTRODUCTION

Use of encapsulated Iodine-125 seed ($T_{1/2}=60\,d$ and mean photon energy 28.4 keV) has been wide spread for the permanent implants of prostate,[1,2] pancreas,[3] and lung.[4] In the past few years, high activity Iodine-125 seed sources have been used with renewed interest for removable implants of breast,[5,6] head and neck,[7] glioblastoma,[8] and ophthalmic tumors.[9] Low-energy photons emitted by Iodine-125 seeds enhance the therapeutic ratio compared to Iridium-192 and Cesium-137 photons and reduce radiation exposure to radiation oncology personnel and nurses.

The original Iodine-125 source (Model 6701) from 3M Company, St. Paul, MN, contained a gold sphere of 0.6-mm diameter as a radiographic marker between two 0.6-mm-diam ion exchange resin balls impregnated with Iodine-125 and encapsulated by 0.05-mm-thick Titanium shell with ends welded. The seed has a nominal length of 4.5 mm and a diameter of 0.8 mm. Due primarily to the presence of thick end welds, the photon fluence distribution around Model 6701 was very anisotropic. In addition, the movement of the gold ball within the hollow titanium tube and variation in the thickness of end welds made the radiation fluence anisotropy around the seed very unpredictable which lead to inconsistent activity calibration and inaccurate dosimetry and treatment planning. In order to overcome these difficulties and to enhance radiographic visualization a new design Iodine-125 seed source (Model 6711) was introduced in 1983 by 3M Company. The new seed, as illustrated in Fig. 1, consisted of a silver rod with Iodine-125 absorbed on the surface and contained in a titanium tube of dimensions similar to Model 6701 seed. A primary objective of the new design was to increase the photon fluence isotropy around the source which could not be improved due to the presence of welded ends.[10] Spectroscopic analysis using an intrinsic Ge detector showed the presence of characteristic x rays at energies 27.4 and 31.4 keV, γ photons at 35.5 keV and 22.1 and 25.2-keV fluorescent x rays from silver wire. The fluorescent x rays from silver, which were not present in the original Iodine-125 seed (Model 6701), account for about 20% of the total photon spectrum and lower the average energy to 27.4 keV (Ref. 10). This resulted in a faster fall off in dose for Model 6711 seed compared to Model 6701 seed. In order to improve the photon fluence anisotropy, a new Iodine-125 source has been developed recently. This paper presents the photon spectral characteristics and its dependence on source orientation for this new Iodine-125 source.

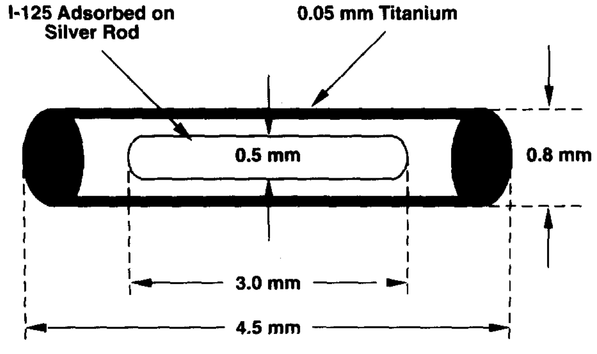

FIG. 1. Model 6711 Iodine-125 source design consisting of a silver rod radiographic marker.

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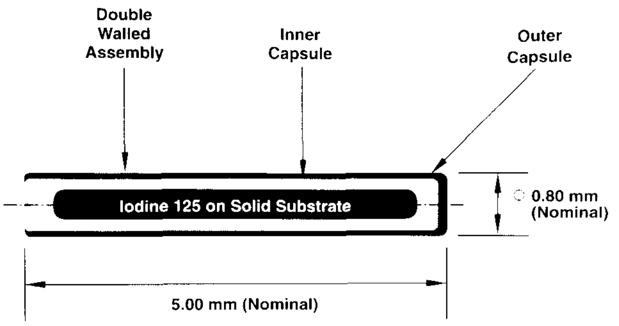

FIG. 2. Best Industries double wall Iodine-125 source of new design consisting of a tungsten filament for radiographic visualization.

II. METHODS AND MATERIALS

The physical characteristics of the new Best 2300 Series Iodine-125 source (Best Industries, Inc.) are shown in Fig. 2. The seed has a length of 5.0 mm and an outer diameter of 0.8 mm. Iodine-125 solution is coated on the surface of a 0.25-mm-diam tungsten wire x-ray marker used for radiographic visualization. The seed encapsulation consists of a 0.075-mm-thick double wall titanium cylindrical shell of uniform thickness all around. As a consequence of double wall encapsulation design of 0.075-mm thickness, the new seed may offer greater structural strength during repeated clinical use. This design may also minimize the possibility of radioisotope leakage due to seed rupture during handling.

For the measurement of the photon spectral characteristics, the Iodine-125 seed was mounted on a precisely machined jig consisting of a thin plastic rod which could be rotated through 360°. The experimental setup is shown in Fig. 3. The seed was placed approximately 1 m from the detector face and from other scattering surfaces. The active area (15.4 cm^2) of the detector subtends a solid angle of 2° at the seed location. Under this geometry of high angular resolution, the photon spectrum was measured with an intrinsic Germanium (Ge) detector (0.38 cm thick). The pulse signal from the detector was entered into a preamplifier and an amplifier and analyzed by a calibrated multichannel analyzer. The energy calibration of the multichannel analyzer was accomplished with an Americium-241 source that emits six photons of varying relative intensities between 11.9 and 59.54 keV (Ref. 11). Measurement of the relative intensities of photon peaks emitted by Iodine-125 seed was made for a fixed value of live time which eliminates the need for an explicit dead time correction to the data.

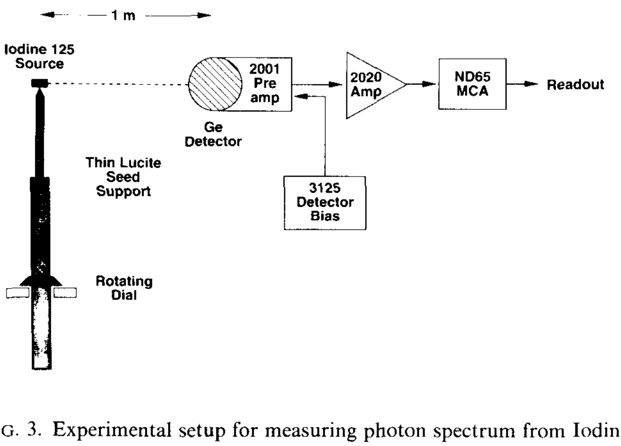

FIG. 3. Experimental setup for measuring photon spectrum from Iodine-125 seed using intrinsic germanium detector.

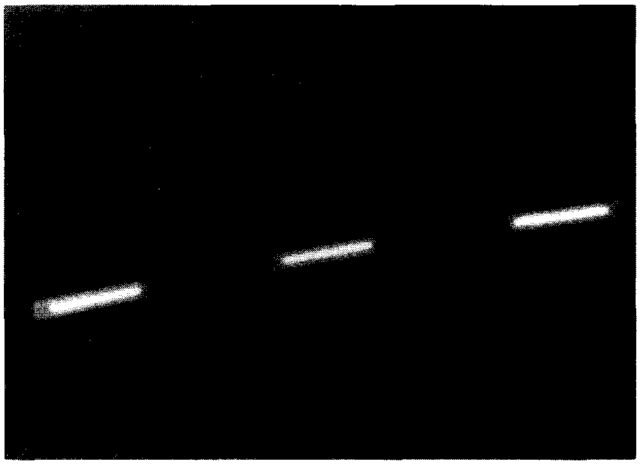

FIG. 4. Radiograph of tungsten marker Best seeds embedded in a 15-cm-thick polystyrene phantom.

The individual photon peaks from Iodine-125 source can be easily resolved by the Ge detector due to its inherent superior energy resolution. The high detection efficiency of the semiconductor detector facilitates the use of low activity seeds that are used clinically. In this study seeds of 1.3–3.8 U air kerma strength were used. Iodine-125 sources are rotated along both seed short and long axes to measure the angular dependence of emitted radiation fluence. The photon spectrum at each seed orientation was measured and stored for analysis. The data presented in this study represent average over several seeds.

III. RESULTS

A. Radiographic visualization

The Best Series 2300 source uses a thin tungsten ($Z = 74$) wire as a radiographic marker compared to Model 6711 seed which incorporates a silver ($Z=47$) rod. For visualization on a radiographic simulation film, the photoelectric interaction is the predominant mode by which low-energy (< 120 kV) photons interact with the seed marker. Due to the higher Z value for tungsten compared to silver, the new design seed does not require a thick marker wire. Figure 4 displays a radiograph of the Best Iodine-125 sources embedded in a 15-cm-thick polystyrene phantom. The seeds are clearly visible. The tungsten marker is 4.0 mm long making it easier to determine the seed orientation. Seed orientation information is necessary if anisotropic dose distribution around Iodine-125 seeds is to be incorporated for accurate dose computation for volumetric implants.

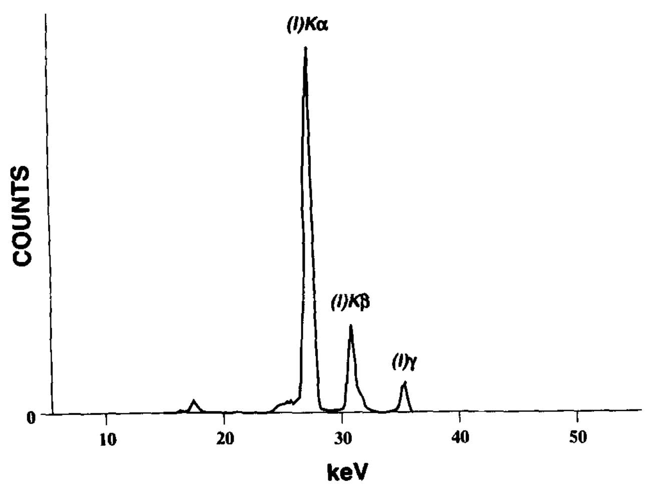

FIG. 5. Best Series 2300 Iodine-125 source photon spectrum detected by a germanium detector. Spectrum was measured along a direction lateral to source long axis.

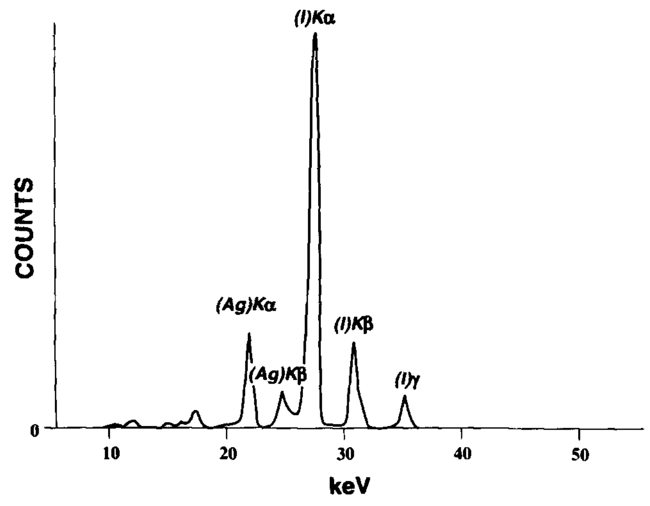

FIG. 6. Model 6711 Iodine-125 source photon spectrum detected by a germanium detector. Spectrum was measured along a direction lateral to source long axis. (Ag) K_α and Ag (K_β) are the two fluorescent x rays originating from the silver marker.

B. Photon spectrum

The photon spectrum emitted by the Best Series 2300 Iodine-125 source, measured by the intrinsic Ge detector, is presented in Fig. 5. The spectrum detected along a direction transverse to seed long axis consists of three resolvable photon peaks. The 27.4-keV K_α x rays, 31.4-keV K_β x rays, and 35.5-keV γ photons are produced during the transformation of Iodine-125 to an excited state of Tellurium-125 by electron capture. The full width at half maximum (FWHM) for each peak is approximately 0.7 keV. Two additional photon peaks at 21.3 and 17.4 keV are produced by the escape of Ge K-characteristic x rays from the detector when 31.4 and 27.4-keV x rays from Iodine-125 interact with Ge. The photon spectrum exhibited by the Best seed and Model 6701 seed are similar. For comparison the photon spectrum emitted by Model 6711 Iodine-125 source in the transverse direction is shown in Fig. 6. In addition to the three Iodine-125 photons, the spectrum contains 22.1-keV K_α and 25.2-keV K_β fluorescent x rays produced from the interaction of the Iodine-125 photons with silver marker. The photon peaks at 12.0 and 17.4 keV are the escape peaks resulting from the loss of Ge K-characteristic x rays. The photons originating from silver rod account for approximately 20% of the total photon fluence emitted by Model 6711 seed in the seed transverse direction[10] and reduce the average energy of the spectrum to 27.4 keV.

C. Photon fluence distribution

The angular dependence of the photon fluence intensity radiated by the Best source in a plane containing the seed long axis is shown in Fig. 7. The data were obtained by rotating the seed along its short axis and measuring the net counts in each photon peak as a function of the angle between the seed long axis and the direction of Ge detector. The counts were collected for a fixed live time value to eliminate dead time corrections. The photon intensity of the three peaks is plotted in polar coordinates where the radial distance from the center represents the relative magnitude of photon fluence in various directions with respect to the seed axis. Angles 0° and 180° correspond to seed long axis and 90° and 270° are along a direction transverse to seed long axis. Between 0° and 30°, the spectrum was collected every 5° and between 30° and 90° every 15°. The relative photon fluence presented in Fig. 7 is normalized to 100% along the seed transverse direction (90°) and represents average data obtained from seven seeds.

The radiation intensity is within 10% of the maximum intensity between seed orientations of 45° and 90°. For angles between 45° and 10°, the photon fluence decreases continuously reaching a minimum value of approximately

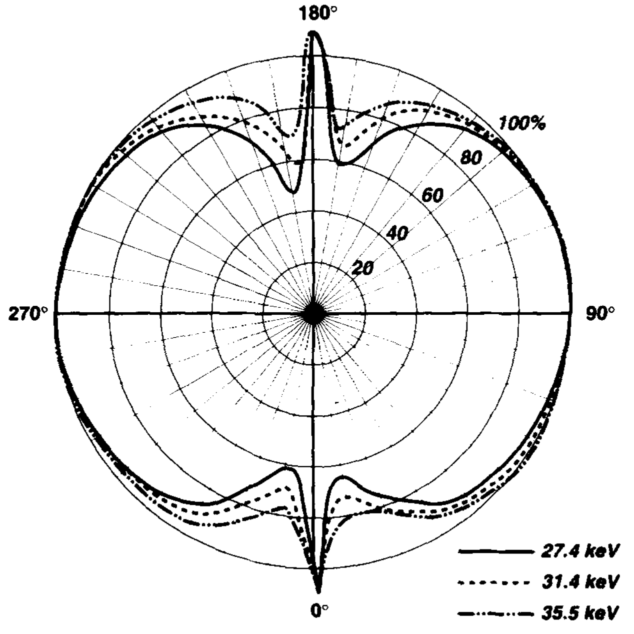

FIG. 7. The angular dependence of photon intensity corresponding to 27.4-keV K_α x rays, 31.4-keV K_β x rays and 35.5-keV γ photons from Best Iodine-125 source.

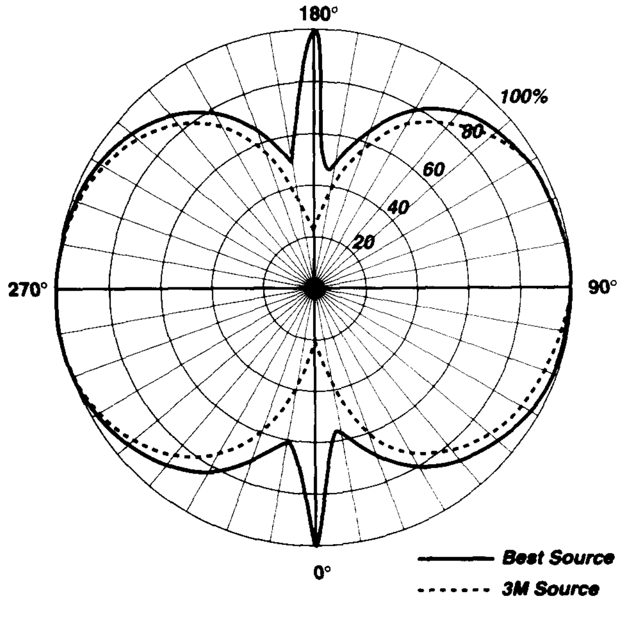

FIG. 8. Comparison of the angular dependence of total photon intensity from Best and Model 6711 Iodine-125 sources.

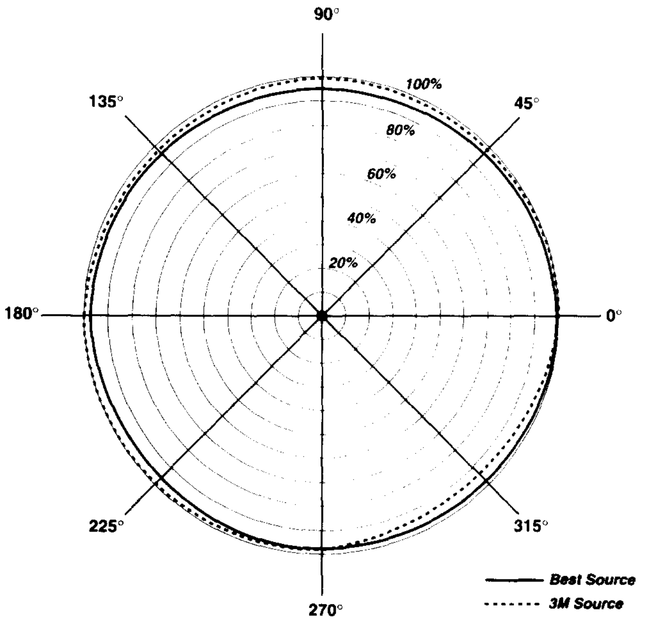

FIG. 9. Comparison of radial distribution of total photon fluence from Best and Model 6711 Iodine-125 sources in the equatorial plane.

60% at 10° due to increasing self-attenuation in the source and oblique filtration through double wall titanium encapsulation. In a narrow cone of ± 10° along the source long axis, the photon intensity increases along the seed axis as the photons travel perpendicular to the encapsulation thickness. The radiation fluence intensity emanating from the seed along 0° orientation is approximately equal to the intensity at 90°. The three photon peaks emitted by the Iodine-125 seed show similar dependence on seed orientation. As expected on theoretical grounds the largest variation is exhibited by the lowest energy photons.

The angular dependence of total photon fluence corresponding to 27.4-keV K_α x rays, 31.4-keV K_β x rays and 35.5-keV γ photons radiated by new seed is shown in Fig. 8. For comparison the total photon fluence for each of the above-mentioned photon energies from Model 6711 seed is also displayed. The greatest difference in the two seed designs appears near the seed long axis. The Best Series 2300 Iodine-125 source with uniform encapsulation thickness all around radiates more photons compared to Model 6711 seed with welded ends in a zone of ± 10° around the seed long axis. Whereas for Model 6711 design, the photon intensity along the source ends is only 21% of the transverse intensity, the new design Best source emits approximately 100% of the intensity along the seed long axis. In the equatorial plane, the radiation source should radiate photons isotropically if the absorption of Iodine-125 on the radiographic marker is uniform. This was confirmed by rotating the seed along its long axis. As shown in Fig. 9, the radiation fluence from the Best seed is very isotropic and comparable to that from Model 6711 source. It has been reported in the literature that deposition of AgI on silver rod in Model 6711 source may be sufficiently nonuniform to produce approximately 20% variation in radiated intensity in the seed equatorial plane.[12]

An estimate of the degree of photon fluence anisotropy is given by the anisotropy factor "AF." It is computed as the ratio of the integrals of the anisotropic to isotropic (point source) dose distributions summed over 4π geometry over the surface of a sphere of radius r:

$$\mathrm{AF}=\frac{\int D_{\text{aniso}}(r,\Omega)\,d\Omega}{\int D_{\text{point}}(r,\Omega)\,d\Omega}.$$

For the Best Iodine-125 source the total fluence anisotropy factor was calculated to be 0.92 (Table I). The 4π-averaged radiation fluence is approximately 8% less than that in the direction lateral to seed long axis. For Model 6701 and 6711 seeds, the photon fluence anisotropy factors are 0.86 and 0.87, respectively (Table I).[10] Shown in Table II are the anisotropy factors for the 27.4-keV K_α and 31.4-keV K_β x rays and 35.5-keV γ photons emitted by the Best seed. These values are 0.91, 0.94, and 0.95, respectively. It is expected that the anisotropy factor would approach unity as the photon energy increases due to reduced attenuation in source material and surrounding encapsulation. The "in air" measured anisotropy factors for Iodine-125 seed will be different when the sources are implanted in tissue. Preliminary measurements by R. Nath[13] on Best Iodine-125 seeds using TLD detectors embedded in a solid

TABLE I. The total phonon fluence anisotropy factors for 3M Models 6701 and 6711 and Best Series 2300 Iodine-125 sources.

Iodine-125 source	Photon fluence anisotropy factor
Model 6701	0.86
Model 6711	0.87
Best Industries	0.92

TABLE II. The anisotropy factors for the 27.4-keV K_α and 31.4-keV K_β x rays and 35.5-keV γ photons emitted by the Best source.

Photon energy (keV)	Source	Best Iodine-125 source photon fluence anisotropy factor
27.4	K_α	0.91
31.4	K_β	0.94
35.5	γ	0.95

water phantom indicate that the new design seed produces more isotropic dose distribution than Model 6711 sources.

IV. DISCUSSION

A new Iodine-125 source has been developed for clinical use with several desirable characteristics. Brachytherapy sources emitting low-energy photons exhibit considerable photon fluence anisotropy with source orientation as a consequence of self-absorption within the radiographic marker and encapsulation jacket. This problem has been minimized by containing the radiographic marker in a double wall encapsulation of uniform thickness all around. The inconsistent anisotropic photon distribution from Model 6711 Iodine-125 source is primarily caused by different thicknesses of end welds which also leads to variation in source length. The photon fluence distribution from Best Series 2300 Iodine-125 source is more isotropic than that from Model 6701 or Model 6711 seeds as measured by anisotropy factor. Use of a thin tungsten filament instead of silver as a radiographic marker leads to the emission of a pure Iodine-125 photon spectrum which is not degraded by marker generated fluorescent x rays. The new seed has good radiographic visualization for seed identification and incorporation of seed orientation information for treatment planning. The new Iodine-125 source may also have enhanced structural strength due to the double wall encapsulation design of greater thickness.

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