Impact of source-production revision on the dose-rate constant of ^{131}Cs interstitial brachytherapy sources

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Purpose: Since its introduction in 2004, the model CS-1 Rev.1 ^{131}Cs source has been used in many radiation therapy clinics for prostate brachytherapy. In 2006, this source model underwent a Rev.2 production revision. The aim of this work was to investigate the dosimetric influences of the Rev.2 production revision using high-resolution photon spectrometry.

Methods: Three CS-1 Rev.1 and three CS-1 Rev.2 ^{131}Cs sources were used in this study. The relative photon energy spectrum emitted by each source in the transverse bisector of the source was measured using a high-resolution germanium detector designed for low-energy photon spectrometry. Based on the measured photon energy spectrum and the radioactivity distribution in the source, the dose-rate constant (Λ) of each source was determined. The effects of the Rev.2 production revision were quantified by comparing the emitted photon energy spectra and the Λ values determined for the sources manufactured before and after the production revision.

Results: The relative photon energy spectrum originating from the principal emissions of ^{131}Cs was found to be nearly identical before and after the Rev.2 revision. However, the portion of the spectrum originating from the production of fluorescent x rays in niobium, a trace element present in the source construction materials, was found to differ significantly between the Rev.1 and Rev.2 sources. The peak intensity of the Nb K_α and Nb K_β fluorescent x rays from the Rev.2 source was approximately 35% of that from the Rev.1 source. Consequently, the nominal Λ value of the Rev.2 source was found to be greater than that determined for the Rev.1 source by approximately $0.7\% \pm 0.5\%$.

Conclusions: A significant reduction (65%) in relative niobium fluorescent x-ray yield was observed in the Rev.2 ^{131}Cs sources. The impact of this reduction on the dose-rate constant was found to be small, with a relative difference of less than 1%. This study demonstrates that photon spectrometry can be used as a sensitive and convenient tool for monitoring and for quantifying the dosimetric effects of brachytherapy source-production revisions. Because production revision can change both the geometry and the atomic composition of brachytherapy sources, its dosimetric impact should be carefully monitored and evaluated for each production revision. © 2010 American Association of Physicists in Medicine. [DOI: [10.1118/1.3453766](https://doi.org/10.1118/1.3453766)]

Key words: dose-rate constant, cesium-131, photon energy spectrum, production revision, brachytherapy

I. INTRODUCTION

Since 2004, the model CS-1 Rev.1 ^{131}Cs source (IsoRay Medical Inc., Richland, WA) has been used by many radiation therapy clinics for prostate brachytherapy. This source has since undergone a production revision in 2006, designated as Rev.2 by the manufacturer.¹ The Rev.2 source is currently used in the treatments of ocular melanoma and head and neck cancers in addition to prostate cancer. While dosimetric characterizations for the Rev.1 and Rev.2 sources have been reported separately by several research groups,^{1–5} none of these reports have examined the effects of the Rev.2 revision by including the Rev.1 and Rev.2 sources in the same study. The aim of this work was to investigate the utility of high-resolution photon spectrometry for quantitative assessment of the dosimetric impacts of source-production revisions, using the ^{131}Cs source as an example.

The need for such an investigation is driven primarily by

the fact that low-energy photons emitted by ^{131}Cs , ^{125}I , or ^{103}Pd can be absorbed and/or scattered easily by the internal structures of a brachytherapy source and the source encapsulation.⁶ In particular, as the photons traverse through the source construction materials, photoelectric interactions occurring in certain materials can generate additional fluorescent x rays that can significantly alter the dosimetric characteristics of the source. For example, the use of silver as radiographic markers in some ^{125}I sources is known to produce a significant amount of silver fluorescent x rays with energies lower than those emitted by ^{125}I . As a result, the dose-rate constant of such a source can be reduced by as much as 6% compared to ^{125}I sources that contain no silver.^{6,7} Indeed, it is suggested⁵ that an earlier production revision (from Rev.0 to Rev.1) of the model CS-1 ^{131}Cs source could be responsible for a 15% difference observed between the dose-rate constants of the Rev.0 (Ref. 8) and Rev.1 (Ref. 2) sources.

Fig. 1. Schematic diagrams of the model (a) CS-1 Rev.1 and (b) CS-1 Rev.2 nominal source geometries.

Second, although a first-order estimation of the dosimetric impact of the Rev.2 production revision might be obtained by comparing the dosimetric characterizations reported separately for the Rev.1 and Rev.2 ^{131}Cs sources, these reports were not designed for accurate quantification of the dosimetric effects of production revision. Specifically, none of these reports examined the pre-Rev.2 and post-Rev.2 sources using the same dosimetry technique, in order to minimize the influence of systematic uncertainties of different dosimetry techniques. In addition, those techniques with large experimental uncertainties are not appropriate for such a study. For example, uncertainties in the Λ determined by thermoluminescent dosimetry are approximately 8%–10% at one standard deviation and 16% at the 95% confidence level.⁹ On the other hand, the Monte Carlo simulation technique has much smaller uncertainties. It would be ideal for such a study if the changes in geometry and atomic composition arising from a production revision are exactly known. For the ^{131}Cs sources, unfortunately, only changes in nominal geometry were available for the prerevision and postrevision sources. No information is publicly available regarding the exact atomic composition of the Rev.1 and Rev.2 sources.

Since the dosimetric characteristics of an encapsulated source are fundamentally determined by the photons emitted by the source, the photon energy spectra measured directly from the prerevision and postrevision sources over a 4π space would embody all the modifying effects of geometric and material compositional changes on the emitted photons. In particular, the photon energy spectrum measured along the transverse axis of the source provides a convenient marker to be used in this work for quantitative assessment of the changes in dose-rate constant induced by source-production revisions.

II. METHOD AND MATERIALS

The nominal source geometry is depicted in Fig. 1(a) for the Rev.1 source and in Fig. 1(b) for the Rev.2 source. As shown in the schematic drawings, the changes in nominal source geometry were very small. However, no information is publicly available on the exact atomic composition of source construction materials for the Rev.1 and Rev.2 sources. The photon energy spectra and the dose-rate constants measured from three CS-1 Rev.1 and three CS-1 Rev.2 ^{131}Cs sources were used in this work to assess the dosimetric

effects of the Rev.2 production revision. The photon energy spectrum emitted along the transverse axis of each source was measured in air using a high-purity germanium spectrometer established for low-energy photon-emitting brachytherapy sources.¹⁰ The calibration and validation of the spectrometry system and its use in the determination of the dose-rate constant for brachytherapy sources have been described in detail by Chen and Nath¹⁰ and will not be reproduced here. The relative spectra of the three Rev.1 sources were measured in our 2005 study using the same photon spectrometry system.² Before measuring the relative spectra for the Rev.2 sources, the constancy of the spectrometry system for relative photon energy spectrum measurement was checked and confirmed using our ^{133}Ba calibration source. The relative spectrum measured by the spectrometer was virtually identical to that measured in 2005 for the ^{133}Ba calibration source.

III. RESULTS AND DISCUSSION

Figure 2 compares the measured in-air raw photon energy spectra (pulse-height distributions) emitted by ^{131}Cs sources before and after the Rev.2 production revision. The spectral peaks arising from the principal ^{131}Cs photon emissions (K_α and K_β x rays) are indicated with red labels. The fluorescent x-ray peaks labeled in blue are those resulting from the interaction of ^{131}Cs photons with the source construction materials, and peaks labeled in black are those resulting from the interaction of ^{131}Cs photons with the detector construction materials. The other spectral peaks are the x-ray escape

Fig. 2. Comparison of the photon energy spectra emitted by the CS-1 Rev.1 and CS-1 Rev.2 sources. The two spectra were normalized to the ^{131}Cs K_α peak.

TABLE I. Relative photon energy spectra measured before (CS-1 Rev.1) and after source revision (CS-1 Rev.2).

Radiation source	Energy (keV)	Relative energy spectrum		
		Bare source ^a	CS-1 Rev.1	CS-1 Rev.2
¹³¹ Cs L	4.1	0.143	0.0	0.0
Fluorescent Nb K_{α}	16.6	...	$0.007 \pm (<0.001)$	$0.003 \pm (<0.001)$
Fluorescent Nb K_{β}	18.7	...	$0.003 \pm (<0.001)$	$0.001 \pm (<0.001)$
¹³¹ Cs K_{α}	29.7	1.0	1.0	1.0
¹³¹ Cs $K_{\beta 1, \beta 3}$	33.6	0.178	0.201 ± 0.007	0.202 ± 0.007
¹³¹ Cs $K_{\beta 2}$	34.4	0.036	0.050 ± 0.002	0.050 ± 0.002

^aNational Nuclear Data Center, information extracted from the NuDat database, <http://www.nndc.bnl.gov/nudat2>, version 2/6/2007.

peaks (not labeled for clarity of presentation) arising from the Ge fluorescent x rays escaping the detector volume. The fluorescent x-ray peaks at 6.4, 8.0, and 8.9 keV were found to originate from the protective steel end-cap of the detector and traces of copper in the detector assembly.¹⁰ These peaks were excluded in the determination of Λ . The fluorescent x rays at ~ 4.5 keV originating from the titanium source capsule were also excluded in the Λ determination because they are not included in the NIST air-kerma strength standard for the ¹³¹Cs source.¹¹ Similar spectra differences, as shown in Fig. 2, were seen among each pair of Rev.1 and Rev.2 sources.

To obtain the quantitative photon energy spectrum emitted by a source, the raw spectrum as plotted in Fig. 2 was first corrected by the energy and efficiency responses of the spectrometry system.¹⁰ The peak intensities of the energy-corrected and efficiency-corrected spectrum were then determined by using the Genie 2000 V3.0 spectral analysis tools that came with the spectrometry system. Table I summarizes the relative photon energy spectra measured for the ¹³¹Cs sources. The relative spectrum was obtained by normalizing the measured spectrum to its ¹³¹Cs K_{α} spectral intensity. The uncertainties in the measured relative spectra were estimated according to the method described in Ref. 10, which include both the uncertainties of the spectrometry system and the standard deviation among the three sources included in each group. Table I and Fig. 2 show that the portion of the energy spectrum arising from principal photon emissions of ¹³¹Cs was nearly identical in the transverse bisector before and after the revision. However, the fluorescent x-ray yield, arising from the photoelectric interactions of ¹³¹Cs photons with niobium present in the source construction materials, was significantly lower in the Rev.2 source. The Nb K_{α} and Nb K_{β} x-ray intensities were only about 35% of those measured in the Rev.1 source. The reduction in measured Nb fluorescence could be caused by (1) reduced niobium content in the Rev.2 source, (2) the increased absorption of Nb fluorescent x rays due to changes made to other components of the source, or the combination of (1) and (2). The reduced Nb fluorescent yield from the Rev.2 source has also resulted in an apparent reduction in the Fe K_{α} peak intensity because the x-ray escape peaks arising from Nb fluorescence overlap partially with the Fe K_{α} peak.

The dose-rate constants determined by photon spectrometry for the Rev.1 and Rev.2 sources were 1.066 ± 0.040 and 1.073 ± 0.041 cGy h⁻¹ U⁻¹, respectively. The reduced emission of lower-energy niobium fluorescent x rays from the Rev.2 sources resulted in a slight increase in the nominal Λ value, by approximately 0.7%, from the Rev.1 source. It should be pointed out that the relative difference between the dose-rate constants of Rev.1 and Rev.2 sources is small and is within the uncertainties of the photon spectrometry technique for individual Λ determination. However, the relative spectra measured for the Rev.1 and Rev.2 sources were nearly identical everywhere except the reduction of Nb fluorescence in the Rev.2 source (Fig. 2). This difference in relative spectra was seen among each pair of Rev.1 and Rev.2 sources. We believe that the difference measured between the relative spectra emitted by the Rev.1 and Rev.2 sources is real rather than an accident of statistical uncertainty associated with the spectrometry technique. The small difference in the dose-rate constants of Rev.1 and Rev.2 sources is traceable directly to the reduction in Nb fluorescent x-ray yield.

The ability to measure this small difference in Λ between the two source models lies fundamentally with the experimental approach adopted in this study and partly with the features of the photon spectrometry technique. In this study, the dose-rate constants of the Rev.1 and Rev.2 sources were determined using the *same* photon spectrometry equipment and analysis method. By making the source model as the main variable, the influence of systematic uncertainty associated with the dosimetry technique and analysis method on the measured $(\Lambda_{\text{Rev.2}}/\Lambda_{\text{Rev.1}} - 1)$ was minimized, as further illustrated in the following uncertainty analysis.

For an individual source, the uncertainty in Λ determined by photon spectrometry came from the uncertainties associated with the measured relative photon energy spectrum and with the fundamental quantities used in Λ computation. Uncertainties in the measured relative energy spectrum arose from (1) source positioning inaccuracy (Type A: 0.5% in relative spectral intensity, estimated from measurements performed with a source placed at various locations within a 1 cm diameter circle around the designated location in the source holder), (2) uncertainties in energy calibration for the spectrometer (Type B: 0.15% in energy, arising primarily

from the finite resolution of the multichannel analyzer), and (3) uncertainties in energy-response calibration for the spectrometer (Type B: 3.3% in the stated activity of calibration sources and 1.4% in efficiency from curve fitting procedure). Uncertainties are also associated with the fundamental quantities including (a) mass energy absorption coefficients (Type B: 2%), (b) Monte Carlo calculated energy buildup factors (Type B: 2%–3%), and (c) mass attenuation coefficients (Type B: 2%). For each source model (i.e., Rev.1 or Rev.2), variations in source construction due to manufacturing tolerance should also be taken into account in the estimation of the overall uncertainties in a model-specific dose-rate constant (Type A: 0.1% in Λ based on the three sources used for each model in this study). For each independent Λ measurement, uncertainties identified above all contribute to the overall uncertainty of Λ .

However, when measuring the relative difference of Λ and, in particular, when the Rev.1 and Rev.2 source models were measured using the same instrument and analysis method, uncertainties arising from (2), (3), and (a)–(c) as identified above remained the same or correlated in the measurements for the two source models. Let $\Delta\Lambda_{\text{Rev.1}}^c$ and $\Delta\Lambda_{\text{Rev.2}}^c$ denote the combined correlated uncertainties in $\Lambda_{\text{Rev.1}}$ and $\Lambda_{\text{Rev.2}}$, respectively. Their contribution to the relative uncertainty in $\Lambda_{\text{Rev.2}}/\Lambda_{\text{Rev.1}}$ was given by¹²

$$\begin{aligned} & \Delta(\Lambda_{\text{Rev.2}}/\Lambda_{\text{Rev.1}})/(\Lambda_{\text{Rev.2}}/\Lambda_{\text{Rev.1}}) \\ &= |(\Delta\Lambda_{\text{Rev.2}}^c/\Lambda_{\text{Rev.2}}) - (\Delta\Lambda_{\text{Rev.1}}^c/\Lambda_{\text{Rev.1}})|. \end{aligned} \quad (1)$$

As a result, the correlated uncertainties canceled each other out. On the other hand, the uncertainties arising from source positioning inaccuracy and intersource structural variation were largely random in the measurements for the Rev.1 and Rev.2 sources. They were considered as uncorrelated in the uncertainty analysis for $\Lambda_{\text{Rev.2}}/\Lambda_{\text{Rev.1}}$. Following the standard uncertainty propagation rule for uncorrelated uncertainties, we got $\Delta(\Lambda_{\text{Rev.2}}/\Lambda_{\text{Rev.1}})/(\Lambda_{\text{Rev.2}}/\Lambda_{\text{Rev.1}}) = 0.51\%$. We believe that this is the strength of the photon spectrometry technique: Once the spectrometry system is calibrated and used in the same setting, differences in relative spectra, as small as those shown in Fig. 2 between the Rev.1 and Rev.2 sources, can be detected and their impact on dose-rate constant can be estimated.

IV. CONCLUSIONS

A photon spectrometry study has been performed to examine the dosimetric effects of the Rev.2 production revision for a ¹³¹Cs source model. It was found that this revision has led to a 65% reduction of niobium fluorescent x-ray yield

and a slightly higher dose-rate constant (relative difference $0.7\% \pm 0.5\%$) for the Rev.2 source. This study demonstrates that photon spectrometry, once established, can be used as a sensitive and convenient tool for monitoring potential dosimetric effects of brachytherapy source-production revisions. Because modifications made to the geometry and material composition of low-energy sources can potentially change their basic dosimetric properties, the impact of each source-production revision should be monitored and evaluated carefully.

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