Assessment of the strength of individual ^{192}Ir seeds in ribbons

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Assessing the strength of individual seed-type sources in ribbon assemblies remains a challenge in brachytherapy quality assurance. Geometries to measure a single source in the ribbon usually fail because of low signals if using very thick shielding to block the radiation from the other sources, or contributions from all the other sources if they are not shielded well. A normal well-type chamber with partial lead shielding forming a small slot provides a differential response along the chamber axis that, through a deconvolution/simultaneous-equations technique, sorts the contributions from each source, allowing the derivation of each source's strength. © 1999 American Association of Physicists in Medicine. [S0094-2405(99)03311-8]

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I. INTRODUCTION

Assaying sources used in brachytherapy form a standard of practice. The report of Task Group 40 of the American Association of Physicists in Medicine recommends assay of 10% of a batch of permanently implanted sources, and 10% or two ribbons for sources so configured.¹

The simplicity of assay for a single source contrasts with the difficulty of determining the strength of individual sources comprising a source train. A common approach measures a signal for the entire ribbon wrapped in a loop in a calibrated well chamber, and simply checks the total strength for all the sources combined. Even determining the total strength in that manner requires addressing the geometric response of the chamber to sources positioned in locations other than that used to calibrate the chamber. Self-shielding and source orientation effects also increase the uncertainty in the strength measurement. While such an approach may give some assurance of source accuracy with a uniformly loaded ribbon, modern implant techniques frequently use differential loading. For nonuniform source-strength distributions, the quality assurance evaluation should verify not only the accuracy of the source strength, but that the correct strengths occupy the correct locations as well.

Bernard and Dutreix describe the use of a lead block with a channel for a ^{192}Ir wire below an orthogonal hole running between the source train and a detector. The latter hole serves as a collimator to limit the view of the detector to a small section of the wire at a time to assess the wire's linear activity.² While this approach could be applied directly to a train of ^{192}Ir sources in a ribbon, our experience with this approach encountered very poor correlation between the measured signal and the individual source strengths. Lead

thick enough to reduce sufficiently the contribution from sources other than the one aligned with the measurement hole reduces the sensitivity of the detector and compromises the precision of the measurement.

Modern practice of temporary implants dictates differential loading. Current conceptions of quality assurance suggest that all aspects of treatments that could affect doses should undergo verification. A method to assure correct source strength for individual radioactive seeds in ribbon remains elusive. Simple, straightforward techniques have not worked sufficiently well. The approach of Bernard holds promise but requires two modifications to overcome the difficulties previously encountered: (1) Increasing the signal for the source aligned with the measurement channel, and (2). Accounting for the contribution of the shielded sources to the measurement. The work described in this report addresses these issues.

II. MATERIALS AND METHODS

This investigation used a well-type ionization chamber (reentrant chamber—modified model HDR-1000, Standard Imaging, Middleton, WI) as the detector system. Lead cylinders fill the well above and below an air-filled aperture. A 3.2-mm diameter tunnel through the lead that also penetrated the base of the unit allowed iridium ribbons to pass through the chamber. Figure 1 shows the chamber schematically. The utility of a similar device for assessment of positioning for high dose-rate brachytherapy sources suggested that the equipment might satisfy the modification requirements to Bernard's approach mentioned above. Without the aperture in place, the well chamber exhibits a typical response to source position along its length, with a broad plateau in the

Modified Well-type Ionization Chamber

FIG. 1. The chamber designed for assay of seed-type sources in ribbons (an "eclipse" chamber). The lead cylinders and spacer provide a differential response along the chamber axis.

middle, and decreased sensitivities toward the ends. The lead shielding and aperture produce an additional differential response in the chamber superimposed upon the chamber's usual response as a function of position along the axis of the chamber. This configuration is similar to the HDR quality assurance test tool for the chamber.³ The selection of a 3.9-mm aperture maximized the signal from a 3-mm-long ^{192}Ir source while excluding most of any radiation from neighboring sources. (Section IV addresses this issue further.) The 1.1-cm-thick lead fillers, approximately 3.5 half-value layers, reduce the signal to approximately 8% through attenuation, although geometry and scatter produce signals of about 30% when the edge of the source lies within 0.7 cm of the aperture.

The tests of the device used ^{192}Ir seeds in plastic ribbons. Figure 2 illustrates the configurations for the ribbons. Ribbon 1, called a "standard ribbon," presented a simple standard with 12 sources spaced at centimeter intervals, center-to-center (c-c). Ribbon 2, referred to as a "treatment ribbon," simulates a ribbon from a customized template implant with

a mix of source strengths and spacings. Ribbon 3 represents a ribbon for an endobronchial application, with sources spaced 0.5 cm c-c and differentially loaded with half-strength seeds in the center third of the source train. Two manufacturers (Best Medical, Inc, Springfield VA, and Alpha-Omega Services, Inc., Bellflower, CA) provided identical sets of source ribbons.

For the initial tests, the source ribbons were placed in a very thin polyimide tube marked in millimeter increments. This tube was extended through the tunnel, and then withdrawn by hand, stopping at each millimeter for a reading. The measurements used an electrometer (model 602, Keithley Instruments, Cleveland, OH) on the 10^{-11}A scale, read with a digital multimeter (Fluke 8060 A) connected to the analog outputs in the back of the electrometer. A pause after each millimeter displacement of the source tube allowed the signal to settle before recording. All measurements exclude the background reading with no source in the chamber.

After making measurements for a ribbon, the final seed in the ribbon was removed and passed through the test chamber in the same manner as the entire ribbon to establish the chamber response as a function of source position in the tunnel.

After completing the measurements on a test ribbon, the sources were cut apart and individually calibrated. This procedure used a calibrated well chamber (model WC-2, Precision Radiation Measurements, Nashville, TN). The calibration on the chamber was based on measurements using a ^{192}Ir source calibrated at the National Institute of Standards and Technology, and the same electrometer used for this study. A standard ^{137}Cs seed provided standardization for the well chamber's sensitivity between the time of the chamber's calibration and that of the test seeds.

For a ribbon in a given position in the chamber, each source in a ribbon should contribute to the signal as per its position along the chamber according to the single-source response curve, and in proportion to its strength. As such, the signal becomes the convolution of the ribbon configuration and the single-source response, with the latter serving as the convolution kernel. Reversing the process, from the measured signal as a ribbon passes through the chamber, deconvolution using the kernel should produce the ribbon configuration.

The kernel profile also carries the information on absolute strength by normalizing the signal to the assayed strength of the seed used for the determination. Thus, the deconvolution results in a mapping of the position and strength of each source in the tested ribbon.

Test Ribbons for Characterizing the Eclipse Chamber

FIG. 2. The source ribbons used for testing the chamber shown in Fig. 1.

III. RESULTS

The broader line in Fig. 3 shows the signal for one of the ribbon 1 configurations as the ribbon passed through the chamber. The general shape peaks in the middle indicating that seeds behind the lead still contribute to the signal assigned to the seed aligned with the spacer.

Figure 4 displays the response of a single source passing

FIG. 3. Sample signal measured for a ribbon of pattern 1 of Fig. 2 (uniform strength seeds separated by centimeter intervals) shown as a broad line. The narrow line displays the signal after deconvolution using the kernel in Fig. 4.

through the chamber. The asymmetry of the signal arises from a displacement of some of the sensitive volume of the chamber by electronics and some additional extracamer volume on one end. The contribution to the signal when the source falls entirely behind the lead shows clearly in this function. The single-source response curve was found to be reproducible between seeds to within $\pm 3\%$. Comparisons of the kernels from the two manufacturers, representing two different source constructions, showed no significant differ-

Deconvolution Kernel

FIG. 4. The deconvolution kernel based on measuring the chamber response to a single source.

ence. The reproducibility for repeated trials with the same source was better than $\pm 2\%$ through the range of the response curve.

An iterative deconvolution technique provided the actual positions of the sources to within 0.5 mm. The true positions differed from the position of the signal peaks due to the contributions of other sources and the asymmetry of the chamber response. However, the deconvolution failed to yield the true source strengths to within $\pm 5\%$. An alternative approach used the positions identified by the deconvolution to designate locations on the raw data curve. At these locations, the signals would be the sum of the products of each source's strength times its kernel value. Thus, for a ribbon of n seeds, the reading, R_k , when source k falls in the center of the space, becomes

$$R_k = \sum_i^n s_i \times k_{k,i}, \quad (1)$$

where s_i = the strength of the source at position i along the ribbon, and $k_{k,i}$ = the contribution to the signal from a source at position k , as indicated by the kernel. The equations for each of the n sources establish a system of simultaneous linear equations, the solution of which yields the source strengths.

Table I compares the values for the source strengths derived from this procedure with that from the measurement in the calibrated well chamber. The columns labeled “% Difference absolute” simply give the difference between the source strengths measured by the two methods as

$$\% \text{ Difference absolute} = \frac{S_e - S_c}{S_c}, \quad (2)$$

where S_e = the strength determined with the eclipse chamber and S_c = the strength measured individually in the calibrated chamber.

The columns labeled “% Difference relative” normalize each reading by the average of the sources in the given train as determined by the given measurement technique. This removes any bias for the calibration to allow evaluation of the relative strengths of the sources in the train. Thus,

$$\% \text{ Difference relative} = \frac{S_e / \bar{S}_e - S_c / \bar{S}_c}{S_c / \bar{S}_c}, \quad (3)$$

where the bar over the quantities indicates the average of all strengths measured with the given technique for the given ribbon.

In all cases, the row indicated as the average displays the absolute value of the differences in the column above. The nonabsolute value for the averages of the relative columns, by definition, would be zeros. The average discrepancy in the source assay was less than $\pm 3\%$, with no discrepancy exceeding 6.5%.

The table shows the results for only one of the treatment ribbons. The measurements of the other ribbon used a different, computer-controlled electrometer that provides an interface to transfer measurements digitally to a computer. This

TABLE I. Source strengths measured with the Eclipse chamber compared to that measured individually in a calibrated well chamber. The columns marked "Relative" relate the discrepancy relative to the average of all strengths, while the columns marked "Absolute" compare the calculated absolute strength of the source to that assayed.

Seed number	Standard ribbons					
	Ribbon A		Ribbon B		Treatment ribbon	
	% Difference relative	% Difference absolute	% Difference relative	% Difference absolute	% Difference relative	% Difference absolute
1	0.1	0.0	0.3	-1.6	-2.0	-3.1
2	3.5	3.4	1.1	-0.7	1.8	0.8
3	6.1	6.1	-1.4	-3.3	-5.4	-6.5
4	1.2	1.2	-1.0	-2.9	-2.5	-3.6
5	-6.3	-6.4	2.5	0.7	2.8	1.8
6	-1.1	-1.1	1.3	-0.6	-0.6	-1.7
7	2.5	2.4	-2.2	-4.1	5.5	4.5
8	-5.5	-5.5	3.1	1.3	1.5	0.4
9	-2.5	-2.5	-1.5	-3.4	-0.9	-2.0
10	-2.1	-2.1	-2.1	-4.0	0.0	0.0
11	3.6	3.6				
Average	3.1	3.1	1.7	2.3	2.4	2.3

electrometer automatically resets the background reading whenever the signal decreased below a built-in threshold, and subtracts the determined background from each signal measured. During the measurement run, the background reset several times, reducing the central readings more than those for the peripheral sources. It was not until after separating the sources for the individual calibrations that this shifting of background was noted in the data. Thus, the measurements for this ribbon yield no useful information—only a lesson.

The signals for the endobronchial ribbons, with 5 mm between centers and 2 mm spaces between source ends, showed no discernable peaks after deconvolution (Fig. 5). This finding reflects the Nyquist frequency, f_n , associated with the aperture size. The 3.9-mm spacer produces a kernel with a full width at half maximum (FWHM) of approximately 4 mm when measured using a 3-mm-long seed. In this setting,

$$f_n = (2 \text{ FWHM})^{-1} = 0.12 \text{ mm}^{-1}. \quad (4)$$

This spatial frequency corresponds to a spacing of $(1/0.12 \text{ mm}^{-1}) = 8.3 \text{ mm}$ between source centers. The spatial frequency of the sources in the endobronchial ribbon becomes

$$f_{\text{endo}} = (\text{period} = 5 \text{ mm center-to-center})^{-1} \\ = 0.2 \text{ mm}^{-1}.$$

This frequency of 0.2 mm^{-1} exceeds f_n and, thus, becomes unresolvable (i.e., there are more cycles per millimeter than the system can distinguish).

IV. DISCUSSION

The experiment demonstrates that a chamber and measurement procedure such as described could provide assays for individual source strengths for ^{192}Ir seeds in ribbons for

most applications where the source centers fall about 8 mm or more apart. Such a test allows verification of differential loading, uniformity of source strength, and a measure of correct spacing.

The manual movement of the ribbons through the detector proves excessively time consuming for the number of ribbons commonly used in a realistic implant. As a test, measurements on one ribbon made use of an automated scanning system (model RFA 300, Therados, Sweden). Replacing the

FIG. 5. The measurement results for an ribbon of pattern 3 in Fig. 2 simulating an endobronchial configuration. The measurement shows no discernable peaks representing the sources. The maximum value simply falls near the center of the ribbon, and the smaller peak to the left is due to the asymmetric chamber response seen in Fig. 4.

glass plate used with the optical densitometer with a board to support the chamber above the phantom tank, clamps attached to the densitometer's scanning arm stretched the ribbon through the chamber and automatically moved it 0.5 mm at a step. The system gated the signal from the chamber into the scanning system's computer at each step, creating the data file of signal vs position. While the automated scan still took about 30 min for a ribbon, this consumed no human's time. Such an automated system, either as a stand-alone device or as an adaptation for automated scanning systems, could provide a feasible method for assuring the accuracy of source strength for interstitial implants.

Resolving the sources in the endobronchial ribbons poses two problems. Differentiating the sources requires resolving the spaces between the seeds. For the test ribbons, this spacing was 2 mm, for a spatial frequency of 0.25 mm^{-1} . Resolving this frequency requires a FWHM, and assumedly an aperture width also of 2 mm. Concentrating on resolving the space between seeds, then, would limit the measurement of the seed strength to sampling parts of the source rather than including all of the source at once, rendering the determination sensitive to variations in activity along the source length and to partial volume artifacts in the calculated total strength. Additionally, many applications like the endobronchial use sources closer than the separation tested, approaching end-to-end. To resolve individual sources in these cases requires smaller apertures still. As the aperture narrows, the signal-to-noise ratio decreases, compromising the accuracy of the actual source assay beyond the sampling problems noted above. These considerations establish the limits for the application of this device.

The signal for these test ribbons peaked at a factor of about 600 times the background signal for sources with strengths of approximately $5\text{ }\mu\text{Gy m}^2\text{h}^{-1}$ (0.7 mgRaed.). Some implants use sources one-sixth of that strength, which still allows for a signal-to-noise ratio of 100. Such would still

allow for assessment of source strength; however, improved signal-to-noise ratio would still be beneficial.

Overall, the approach described worked well for verification of source strength for seeds in ribbons with separations of 8 mm or greater between centers (about 5 mm from end to end). Such configurations account for most of the source trains used clinically. More development remains necessary for verification for source trains with closer spacing. The technique lends itself well to automation, having been adapted to a common computerized beam scanner.

V. CONCLUSION

The well chamber with differential shielding using a deconvolution/simultaneous-equation technique allows assay of individual seed-type sources in ribbons to within an average accuracy of 3%, with no errors greater than 6.5%. The method works for ribbons with seed spacing greater than 8 mm center-to-center, and for uniformly and differentially loaded ribbons. The response of the system remained the same regardless of the manufacturer of the sources. While the method does not work directly for ribbons with spacing of less than 8 mm between source centers, this could serve as a valuable quality assurance tool for most ^{192}Ir interstitial implant source trains.

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