

Dosimetric Benefits of an Adjustable-Energy Electronic Brachytherapy Source

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ABSTRACT

Introduction: An x-ray source was developed of sufficiently small size to allow its entry into HDR catheters. Three features distinguish this device from traditional HDR. Its spectrum is continuous with a 50 keV maximum energy. Low energies enable hospital staff to remain in the treatment room during irradiation. A second distinguishing feature is that radiation is produced only during activation. The third distinction is control of the source's kVp, providing high conformity of dose distributions. Using the source, dwell kVp's and dwell times need to be optimized. This complexity is justified by superior dose distributions this technology offers.

Methods: Two programs were written. One program calculates point doses and the second calculates optimal dwell times and kVp's for meeting desired point doses. Optional constraint points and tolerance doses can be input. The optimizer then attempts to meet the desired point doses while keeping constraint point doses below tolerance. Dosimetry calculations follow the TG-43 formalism using point source geometry. Since kVp is variable, families of radial dose functions and dose rate constants are required. The 2D source anisotropy was found to have minimal energy dependence. Depth dose data were modeled in 2 kVp increments along the anode's bisector. The dose rate constants and radial dose functions were calculated. A single 2D anisotropy table is used for all energies.

Results: The dose conformity favored the tube in all comparative tests with Ir-192 HDR sources.

Conclusion: This x-ray tube has the potential of improving dose conformity of brachytherapy implants.

INTRODUCTION

A new miniature, electronic brachytherapy source was recently developed by Xoft microTube Inc. of Fremont, CA. The x-ray source is sufficiently small to allow entry into implantable catheters. A thin flexible cable permits easy and accurate placement at any location within the catheters. This x-ray tube advances the state of the art of brachytherapy technology.

During the first sixty years of brachytherapy practice, diseased sites were implanted using radioisotopes (usually radium) taken from a limited assortment of fixed air kerma strengths. The dose distributions of these implants were optimized using tabulated loading rules. The planning physicist hoped that the source inventory included the appropriate air kerma strengths dictated by the desired rules. All of the sources were loaded and removed at the same time. The patient was required to remain in shielded isolation for the entire treatment time, typically lasting several days. Once digital computers became readily available, simple optimization methods accounting for available source strengths became feasible.

In the 1960's, HDR afterloaders became commercially available. In conventional HDR brachytherapy, a single radioactive source (usually Ir-192) attached to a wire cable is positioned at several locations in a diseased site. Unlike LDR brachytherapy, the time that the source resides at each dwell position is variable. The HDR afterloader was a major advancement in the field of brachytherapy. With the ability to customize dwell times, HDR is dosimetrically equivalent to LDR brachytherapy, providing sources of any desired air kerma strength. Clearly the radiobiological effects of HDR are not equivalent to LDR however. Dwell times can be optimized using computer algorithms. The dose distributions of optimized HDR treatment plans are consistently superior to comparable LDR implants.

The Xoft microTube Flexible X-ray Probe discussed here represents a further advancement in the state of the art. As with conventional HDR, the x-ray source can be positioned at several locations in the diseased site. A number of important features, however, distinguish this device from standard HDR brachytherapy. Unlike radioisotopes, the energy spectrum generated by this device is continuous with a maximum energy 50 keV. Moreover, the energy spectrum can be altered by changing the anode's kVp, as is done with diagnostic x-ray units. The capability of setting the tube's kVp provides finer control of the dose distributions than is possible using isotope brachytherapy sources. This advantage results from the ability to fine-tune the dwell kVp as well as the dwell time. Since this source emits low-energy x-rays, radiation safety protocols are simplified. Hospital staff can remain with the patient during treatment. A shielded room is not required for using this device, permitting any hospital with OR facilities to easily acquire and assimilate this technology. The source emits radiation only when activated. Since the x-ray probe contains no radioisotope, a radioactive materials license is not required.

Customized dosimetry and optimization algorithms were developed and coded in software for use with the Xoft X-ray Probe. Optimal dwell kVp's must be determined in addition to finding optimal dwell times. This added flexibility demands more sophisticated dosimetry and optimization algorithms.

METHODS

Two computer programs were written for use with the Xoft X-ray Probe. One program calculates reference point doses with defined dwell times and kVp's. The second program determines a set of optimal dwell times and kVp's for achieving the desired doses delivered to the reference points. Optional constraint points and tolerance doses can also be input. In this case, the optimizer attempts to simultaneously meet the desired reference point doses while keeping the doses to the constraint points below the tolerance levels. When constraint points are used, the program prompts the user to input weight values. These weights determine the emphasis the optimizer will place on the reference point and constraint point requirements. In both programs the dosimetry is calculated using an extended TG-43 formalism. The anode dimensions are on the order of 1 mm, justifying the use of point source geometry.

The variable-kVp feature of the source necessarily complicates the dosimetry formalism compared with radioisotopes. Families of radial dose functions and dose rate constants must be applied. As this device operates in the photoelectric region these parameters need to be computed in fine energy increments. The 2D source anisotropy was found to have a small dependence on energy and is assumed to be energy independent for the dose calculations. The dosimetry and optimization algorithms were developed under the assumption that the tube current is kept fixed.

Depth dose data were modeled along the perpendicular bisector of the anode in 2 kVp increments. The peak source voltage ranges from 34-50 kV. In the future, additional peak voltages below 34 kV will be added to the data files. The dose rate constants are in effect the depth dose values for a unit dwell time at a distance of 1 cm from the anode along the perpendicular bisector. The depth dose functions were normalized to unity at a distance of 1 cm. The radial dose functions were determined by dividing the normalized depth dose data by the geometry factor $1/r^2$. A single 2D anisotropy data table is used for all energies.

All of the energy-dependent data were interpolated to 0.1 keV increments to avoid energy interpolation during program execution. Performing this interpolation prior to running the software speeds up the optimizer code while testing different kVp values during execution.

The optimizer is based on a form of genetic algorithm. As the name implies, genetic algorithms attempt to optimize a model by mimicking Darwinian evolution. Simulated natural selection is the driving force of the algorithm. Simulated mutations and interchanging of model parameters among a population of prospective dwell times and kVp's affect the evolutionary optimization process.

RESULTS

The programs were tested on simple planar geometric configurations. Three configurations are shown in Figures 1-3.

Dosimetric comparisons were made between the Xoft X-ray Probe and a Varian VarSource® Ir-192 HDR source. For the comparison, the implant geometries and reference points were kept as close as possible for both the Ir-192 and the Xoft X-ray Probe. Due to the 5 mm extent of the Ir-192 source and the point source model of the tube, there is a slight variation in the source placement. These differences, however, cannot fully account for the differing dose distributions.

In the figures, the yellow squares represent the reference points used for optimization. In each configuration, the desired dose is 5 Gy to all reference points.

Xoft microTube X-ray Probe

Optimized X-ray probe isodose contours are illustrated in Figures 1A-3A. The dose distributions were calculated using the newly developed software.

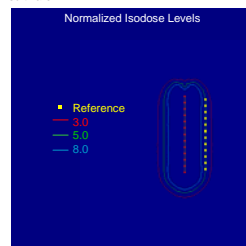


Figure 1A: X-ray Probe isodose contours for a linearly-stepped source

Varisource

The corresponding optimized Varisource isodoses are shown in Figures 1B-3B. The Varisource dose distributions and isodoses were calculated by a Varian CadPlanBT™ RTP system.

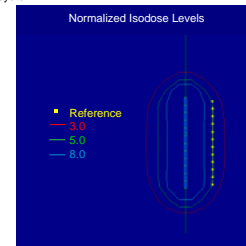


Figure 1B: Varisource isodose contours for a linearly-stepped source

A simple linear source dwell sequence is illustrated in Figure 1. One can see the slightly superior dose conformity of the Xoft X-ray Probe isodoses with the reference points, especially at the ends of the source train.

Normalized Isodose Levels

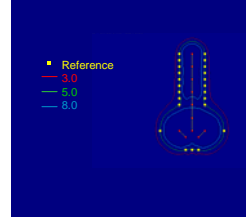


Figure 2A: X-ray Probe simulated GYN isodoses

Normalized Isodose Levels

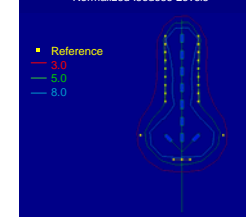


Figure 2B: Varisource simulated GYN isodoses

More marked differences in the dose distributions can be seen in Figure 2. The Varisource prescription isodose does not intersect all of the yellow squares. By comparison, the Xoft X-ray Probe prescription isodose dose intersects each square, indicating superior dose conformity. The low-energy x-rays from the x-ray probe reduce the influence of the more distant dwell positions from each of the reference points.

Normalized Isodose Levels

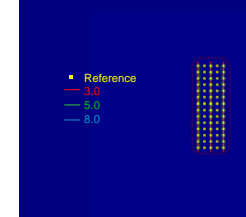


Figure 3A: X-ray Probe planar implant isodoses

Normalized Isodose Levels

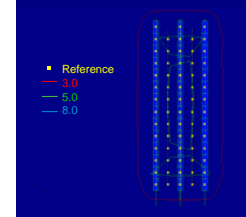


Figure 3B: Varisource planar implant isodoses

A three-catheter planar implant is shown in figure 3. The catheters are spaced 1 cm apart from one another at $x=0.0$, $x=-1.0$ and $x=1.0$. The isodoses were calculated 5 mm from the source plane. The reference points are also 5 mm from the source plane.

RESULTS

The coordinates of the reference points (in cm) and the actual doses received by these points by both radiation sources are tabulated in Tables 1-3. These tables provide a quantitative comparison of the two dose-delivery systems.

Linearly-stepped Source

X	Y	Z	TUBE DOSE	Ir-192 DOSE
1.65	-2.75	0.00	4.96	4.63
1.65	-2.25	0.00	5.08	4.99
1.65	-1.75	0.00	5.01	5.07
1.65	-1.25	0.00	5.02	5.04
1.65	-0.75	0.00	5.03	5.01
1.65	-0.25	0.00	4.93	4.99
1.65	0.25	0.00	5.02	4.99
1.65	0.75	0.00	5.08	5.01
1.65	1.25	0.00	4.98	5.04
1.65	1.75	0.00	4.95	5.07
1.65	2.25	0.00	5.08	4.99
1.65	2.75	0.00	4.96	4.63

Table 1: Comparative reference point doses (Gy) of the X-ray Probe and Varisource Ir-192 HDR sources for a linearly-stepped source

Planar Implant

X	Y	Z	TUBE DOSE	Ir-192 DOSE
-1.00	3.25	0.00	5.10	5.44
-1.00	2.75	0.00	5.18	5.65
-1.00	2.25	0.00	5.10	4.92
-1.00	1.75	0.00	5.10	4.94
-1.00	1.25	0.00	5.11	4.97
-1.00	0.75	0.00	5.11	5.00
-1.00	0.25	0.00	5.11	5.01
-1.00	-0.25	0.00	5.10	5.01
-1.00	-0.75	0.00	5.09	5.00
-1.00	-1.25	0.00	5.08	4.97
-1.00	-1.75	0.00	5.08	4.94
-1.00	-2.25	0.00	5.08	4.92
-1.00	-2.75	0.00	5.16	5.15
-1.00	-3.25	0.00	5.13	5.44

Implant (simulated GYN)

X	Y	Z	TUBE DOSE	Ir-192 DOSE
-2.50	2.00	0.00	4.97	3.48
2.50	2.00	0.00	4.97	3.58
-1.00	4.00	0.00	5.27	4.63
1.00	4.00	0.00	5.27	4.67
-1.00	4.50	0.00	4.63	4.36
1.00	4.50	0.00	4.63	4.38
-1.00	5.00	0.00	5.07	4.30
1.00	5.00	0.00	5.07	4.31
-1.00	5.50	0.00	5.12	4.25
1.00	5.50	0.00	5.12	4.25
-1.00	6.00	0.00	4.99	4.26
1.00	6.00	0.00	4.99	4.26
-1.00	6.50	0.00	4.93	4.34
1.00	6.50	0.00	4.93	4.34
-1.00	7.00	0.00	4.98	4.60
1.00	7.00	0.00	4.98	4.60
-1.00	7.50	0.00	5.09	4.89
1.00	7.50	0.00	5.09	4.89
-1.00	8.00	0.00	4.95	4.56
1.00	8.00	0.00	4.95	4.56
-0.50	0.50	0.00	5.10	6.25
0.50	0.50	0.00	5.10	6.15
0.00	0.50	0.00	4.66	6.28
-0.50	3.25	0.00	4.43	4.69
-0.50	2.75	0.00	4.63	4.92
-0.50	2.25	0.00	4.63	4.82
-0.50	1.75	0.00	4.62	4.89
-0.50	1.25	0.00	4.61	4.88
-0.50	0.75	0.00	4.60	4.86
-0.50	0.25	0.00	4.63	4.89
-0.50	-0.25	0.00	4.62	4.89
-0.50	-0.75	0.00	4.61	4.88
-0.50	-1.25	0.00	4.60	4.86
-0.50	-1.75	0.00	4.57	4.83
-0.50	-2.25	0.00	4.55	4.82
-0.50	-2.75	0.00	4.55	4.92
-0.50	-3.25	0.00	4.35	4.69
-0.50	3.25	0.00	4.43	4.69
-0.50	2.75	0.00	4.63	4.92
-0.50	2.25	0.00	4.63	4.82
-0.50	1.75	0.00	4.62	4.89
-0.50	1.25	0.00	4.63	4.86
-0.50	0.75	0.00	4.63	4.88
-0.50	0.25	0.00	4.63	4.89
-0.50	-0.25	0.00	4.62	4.89
-0.50	-0.75	0.00	4.61	4.88
-0.50	-1.25	0.00	4.57	4.83
-0.50	-1.75	0.00	4.55	4.82
-0.50	-2.25	0.00	4.55	4.92
-0.50	-2.75	0.00	4.55	4.92
-0.50	-3.25	0.00	4.35	4.69
0.00	3.25	0.00	5.03	4.95
0.00	2.75	0.00	5.07	5.22
0.00	2.25	0.00	5.09	5.13
0.00	1.75	0.00	5.10	5.13
0.00	1.25	0.00	5.11	5.15
0.00	0.75	0.00	5.11	5.17
0.00	0.25	0.00	5.11	5.18
0.00	-0.25	0.00	5.10	5.18
0.00	-0.75	0.00	5.09	5.17
0.00	-1.25	0.00	5.07	5.15
0.00	-1.75	0.00	5.04	5.13
0.00	-2.25	0.00	5.03	5.13
0.00	-2.75	0.00	5.00	5.22
0.00	-3.25	0.00	5.04	4.95

Table 2: Comparative reference point doses (Gy) of the X-ray Probe and Varisource Ir-192 HDR sources for the implant shown in Figure 1

Table 3: Comparative reference point doses (Gy) of the X-ray Probe and Varisource Ir-192 HDR sources for a planar implant

Regarding Table 3, both the Varisource and X-ray Probe reference doses conform closely to the reference points exactly overlaying the catheters ($x = -1.0$ and $x = 0.0$) 5 mm from the implant plane. The points where $x = 0.5$ corresponds to the reference points between the catheters 5 mm from the implant plane. The X-ray Probe isodoses conform more closely at the ends of the source trains. For the reference points situated between the catheters ($x = 0.5$), however, the Varisource reference doses conform more closely with the desired values. The penetration of the higher energy Ir-192 gamma rays is greater than the lower energy x-rays generated by the X-ray Probe. This increases the doses to the more distant reference points from the sources.

SUMMARY

These results suggest that for reference points close to the catheters, the X-ray Probe is capable of producing superior dose conformity than is possible with Ir-192.

As the energy of the X-ray Probe radiation is significantly lower than Ir-192, however, it may not be possible to simultaneously match proximal and distal dose requirements as well as with Ir-192.

CONCLUSION

Although the X-ray Probe does not yet have a clinical track record, these results indicate that the Xoft microTube X-ray Probe has the potential of significantly improving the dose conformity of brachytherapy implants.

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