VOLUMETRIC ANALYSIS OF DOSE DELIVERED BY XOFT AXXENT X-RAY SOURCES

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ABSTRACT

Purpose: To study the spatial characteristics of the dose delivered by the Xoft Axxent Electronic Brachytherapy system within a volumetric (voxel) visualization system. Further, to extend the study from tools available in treatment planning systems, which are typically limited to a single set of TG-43 input data for a source type, to look at data for individual sources. Additionally, to allow for comparisons to be made between the standard or average source, and a particular source of interest via difference images, line plots, and histograms.

Method and Materials: Input spatial data in the form of polar and azimuthal angular distributions, and depth dose readings acquired in the course of source characterization, were loaded into a custom LabVIEW program. This program created 3D voxel arrays for an average reference set and for individual sources, allowing two data sets in memory simultaneously. Analyses on the voxel arrays include visualization of the distributions via 2D false-color images and line plots, scatter plots and histograms of values and cumulative values. The visualization tools can be applied to either source or reference data set or the difference between them.

Results: 2D images representing slices through the volume, and line plots along chosen lines on the images, provide information on the spatial variation in either the source data or in the difference, or percent difference, between a specific source and the reference. Histograms provide quantitative results on the degree of variation between source and reference, while scatterplots provide insight into the region or characteristic causing variations.

Conclusion: Volumetric analysis of the Xoft Axxent™ source is a powerful tool for understanding the dose distribution and expected variation from source to source, which can be applied to any brachytherapy source for which 3D spatial data is available.

INTRODUCTION

- Xoft has developed an electronic (non-isotopic) high dose rate brachytherapy device (Axxent™), which is FDA cleared for use in breast brachytherapy. The Axxent™ Electronic Brachytherapy System, consists of the X-ray Source, the Balloon Applicator and the Controller.
- The Xoft Axxent™ HDR X-ray Source comprises an x-ray tube in a multi-lumen catheter that allows cooling fluid to circulate over the tube. The Source delivers tight, conformal doses of x-radiation to the inner surface of a body cavity such as an excised tumor bed and operates at up to 50 kVp and 300 μA. The x-ray tube is ~2.25 mm in diameter by 15 mm long and is attached to a high voltage cable and encapsulated within an electrical ground.
- Treatment planning is performed using commercially-available HDR brachytherapy planning systems using a recommended set of dosimetry parameters in the format specified in the TG-43 protocol. The values are based on measurements and Monte Carlo calculations of spatial characteristics of the dose rate, including polar and azimuthal anisotropy and depth-dose curves. Source geometry details for the calculations are shown in **Figure 1**.
- Manufacturing testing duplicates several of the measurements at a subset of the spatial point grid, to ensure that all sources are consistent with published dosimetry parameters to within the stated uncertainties. Traditionally the pass-fail criteria are based on calculation of maximum deviations from nominal behavior, evaluated independently over the various parameters. While offering a straightforward interpretation of results, this has the disadvantage of not being comprehensive in bringing together the effect of all spatial parameters simultaneously.
- To address this issue, a method of analysis has been developed that looks at the entire spatial data set. From measurements of depth-dose, and of polar and azimuthal asymmetry at several distances from the source, a volumetric data set is constructed using reasonable interpolation schemes. By comparing the voxel array built from the source being evaluated to that representing the TG-43 standard, the deviations of the source from nominal can be evaluated in a more sophisticated way.
- The difference voxel array can be constructed, and the frequency of errors above a certain value entered into a histogram analogous to a DVH, or entered in a scatterplot to study as a function of distance, angle, etc.

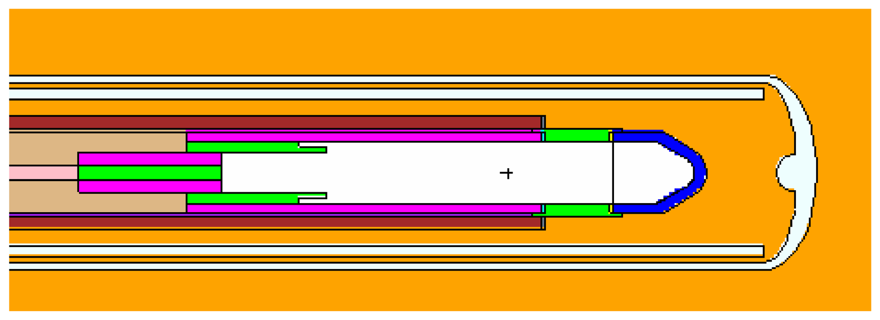

Figure 1. Geometry of the Xoft Axxent™ HDR X-ray Source. Monoenergetic, 50 keV electrons originate from the hot cathode, and travel from left to right in the above diagram.

METHODS

- Dose measurements were made for 20 sources at spatial points surrounding the Xoft Axxent™ X-ray Source to determine anisotropy, azimuthal dependence and depth-dose. From these points, a full volumetric data set was created for each source individually, and for the overall average to create a reference standard. Point by point comparisons of each source to the standard are made in terms of absolute dose difference in Gy, and in percent terms.
- Raw polar, azimuthal and depth-dose data were acquired with custom computer-controlled apparatus with the source immersed in a water bath (11 cm high x 29 cm long x 29 cm wide). Radiation dose was measured with a PTW model 34013 ion chamber encased in a solid water fixture to keep it dry. Linear and radial stepper motors and stages allowed for precision positioning of the detector.
- A 3-d array of points (voxels) was created from input data that took the form of depth-dose data at radii of 10 to 70 mm at 2 mm increments, azimuthal angles in 15 degree steps at radii of 20, 40 and 60 mm, and polar angles in 10 degree steps at radii of 20, 30, 50 and 70 mm. A total of ~ 225 discrete points went into each set. Polar data was missing at the most extreme proximal angles, due to interference of measuring apparatus with the source cable.
- A dedicated LabVIEW program was used to acquire and reduce the data, while a second LabVIEW program was created to carry out the volumetric analysis steps of importing the raw data, constructing the voxel arrays, and creating the analysis output.
- The array was created by linear interpolation of normalized angular data, combined with a double exponential fit to the depth-dose data. The fit had typical RMS errors of less than 2%. Arrays extended ± 40 mm on a side, and had 51x51x51 voxels, for 1.3 x 10^5 points.

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RESULTS

Raw Input Data

- **Figure 2** shows polar data in the form of the TG-43 2d anisotropy function. Data were taken at distances of 20, 30, 50 and 70 mm from the source. The data series represent averages of measurements taken at negative and positive angles. In addition two passes were taken and averaged after confirmation of reproducibility.
- **Figure 3** shows depth-dose data from 10 to 70 mm in 2 mm increments.
- Azimuthal data were also taken, at distances of 20, 40 and 60 mm (not shown here). For the TG-43 standard a perfectly flat distribution was used, as TG-43 does not provide for azimuthal variation.

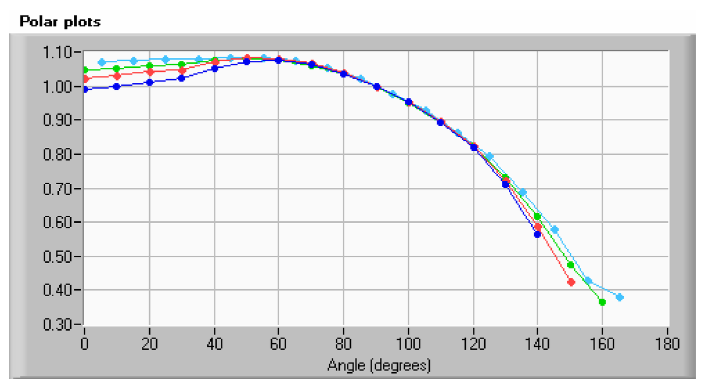

Figure 2. Polar variation of dose rate at radii of 20 (dark blue), 30 (red), 50 (green) and 70 (cyan) mm in terms of the 2d anisotropy function.

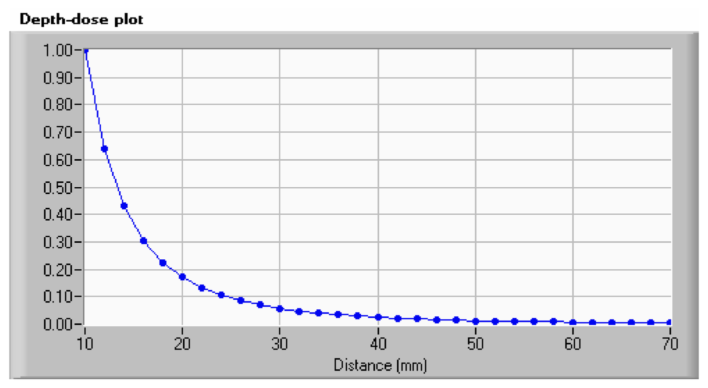

Figure 3. Depth-dose curve for 50 kV operation

False-color Rendering and Line plots of Volumetric Dose Distribution

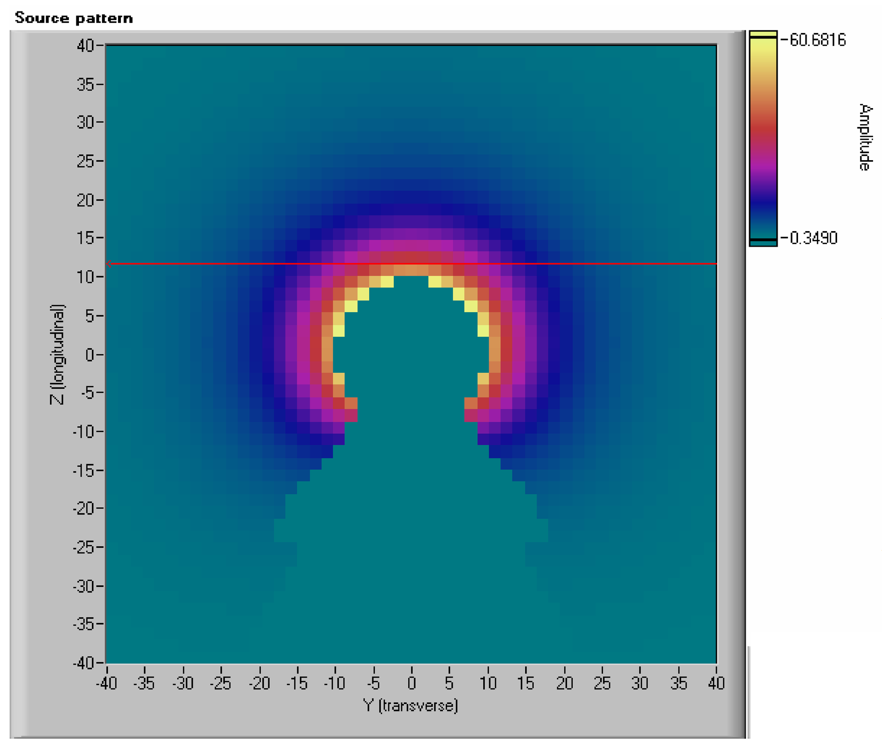

Figure 4. False color image of a slice through the voxel array, in a plane parallel to the source. Source distal position is at top. Data is missing in a 10 mm sphere around the source, and in a volume proximal to it.

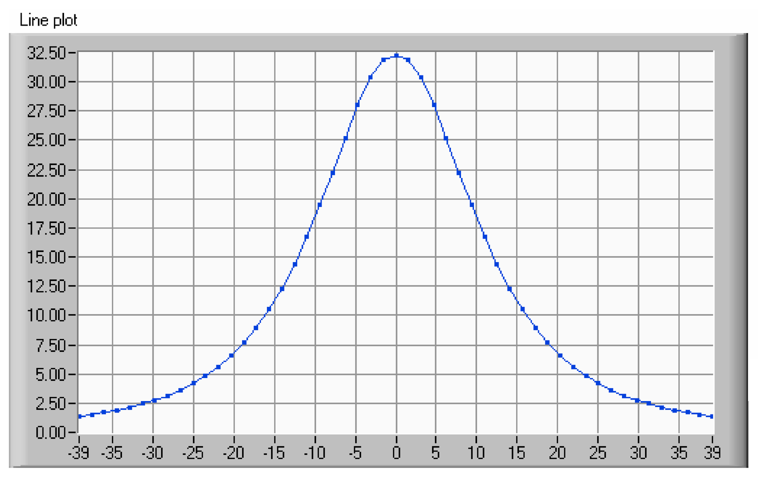

Figure 5. Line plot of dose along the horizontal red line in Figure 4.

- The raw input data is used to construct a volumetric data set, in this case on a 51 x 51 x 51 array of voxels. This can be done for any source for which spatial data is available.
- **Figure 4** is an image of a slice through the center of the volume in the plane of the source. Missing data corresponds to a circle 20 mm in diameter around the source, and an area in the proximal direction where the cable interfered with the measurement apparatus.
- The red horizontal line in the image is the path of a line plot in the following figure (**Figure 5**).
- The absolute dose was normalized to 3.4 Gy at 30 mm from the source. The applicator balloon in this example has a diameter of 40 mm.

Comparison of Individual Sources to the Standard

- A reference standard volumetric data set was built using data from an average of the 20 sources used to create TG-43 reference parameters. For 10 of those sources, arbitrarily chosen, individual data sets were created as well. These were compared to the reference standard by calculating differences point by point, in absolute and in percentage terms. From a treatment planning point of view, these differences can be thought of as potential dose delivery errors.
- The images in **Figures 6 and 7** represent slices near the center of a volume that is the percentage difference between an individual source and the standard. One slice is in the plane of the source, the other is perpendicular to it.

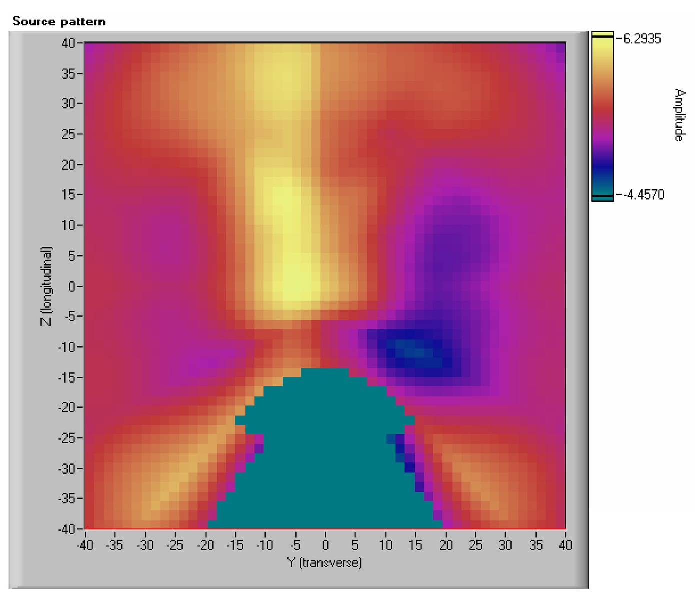

Figure 6. Dose differences in percent between one source and the standard, in a plane parallel to the source axis, off the plane of the source to avoid the balloon dead spot.

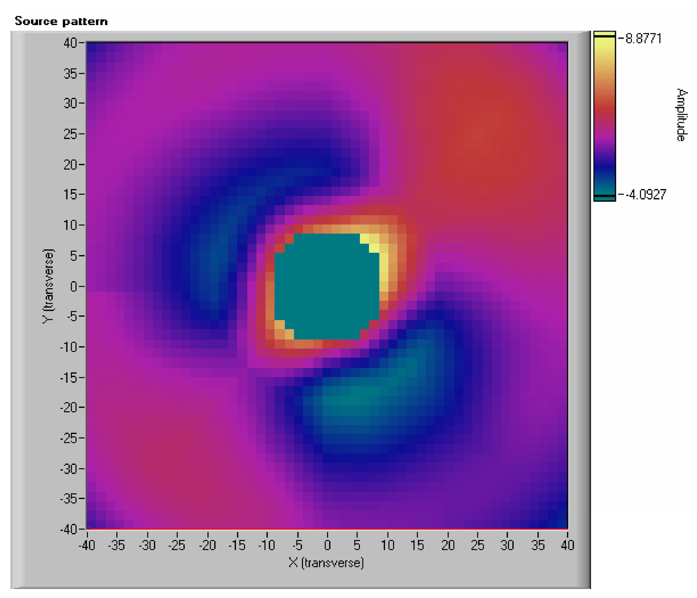

Figure 7. Dose differences in percent between one source and the standard, in a plane perpendicular to the source axis. In this plane the pattern is primarily due to azimuthal variation.

RESULTS

Cumulative Dose Histogram & Error Volume Histogram for Source s/n 3698

Figure 8 shows the percent of voxels receiving a dose of "D" or greater for the reference standard data set. Absolute dose was normalized to 3.4 Gy at 10 mm from a 20 mm radius balloon. The volume within the balloon is excluded from the analysis. Note log scale on vertical axis.

The histogram of **Figure 9** summarizes the frequency of differences (or errors) between a source s/n 3698 and the standard. This is similar to the cumulative dose histogram, but with percent errors as the parameter rather than dose. It shows the frequency of errors to be expected from a given source relative to the treatment plan. In this case 90% of the voxels have an error of 5% or less, and 99% of 8% or less.

This analysis can be performed for each of the sources.

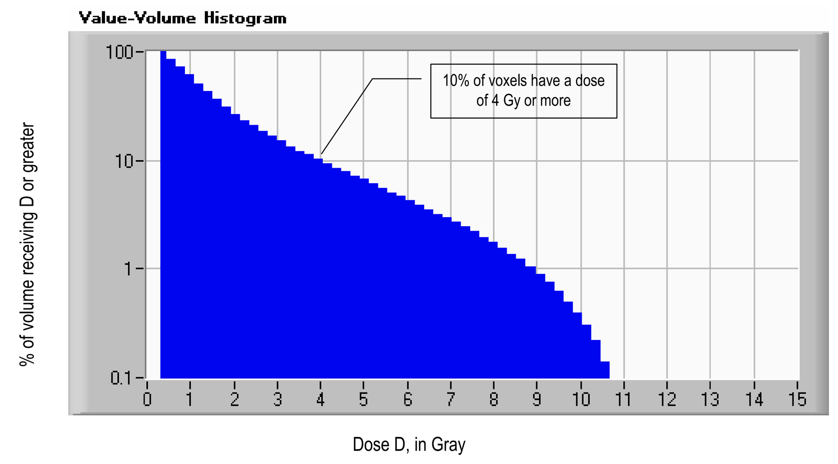

Figure 8. Percent of voxels receiving a dose of "D" or greater as a function of the dose "D".

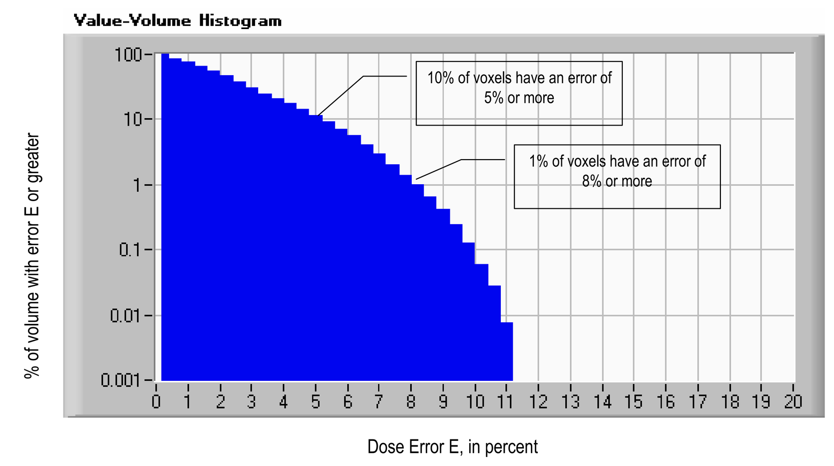

Figure 9. Fraction of voxels with percent errors of "E" or greater for source s/n 3698.

Dose Error Scatterplot

This scatterplot of dose error % versus distance from source (**Figure 10**) shows the behavior of the dose errors. Taking into account that there are fewer voxels at the smaller distances, and also fewer at the very largest (these are in the corners of the cube) the distribution of errors is fairly constant with distance. It arises primarily from polar and azimuthal variations of the individual tube from the standard.

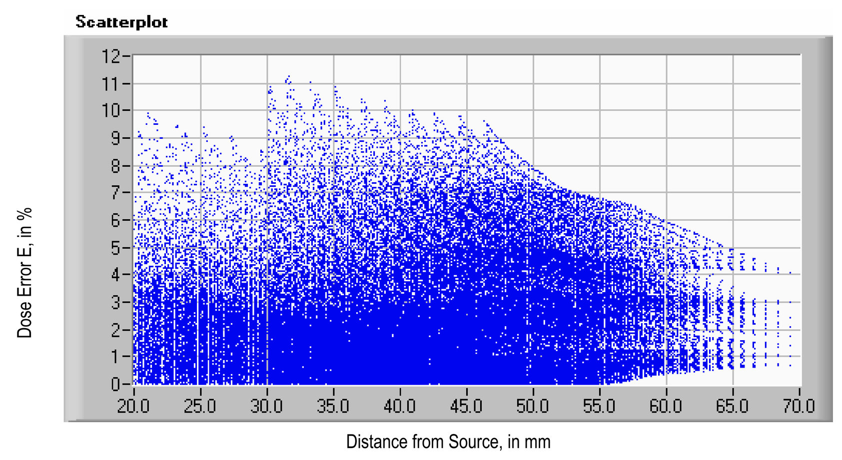

Figure 10. Scatterplot of percent dose error versus distance from source for all voxels, for source s/n 3698. Voxels inside the balloon were excluded.

Error Volume Histogram for 10 Sources

Figure 11 shows a summary of the error volume histogram for 10 sources, plotted together as line graphs. The average of all 10 is given by the thick black line. 90% of voxels have an error less than 5.4%, and 99% have an error less than 9%. All are well within the error budget of 20%.

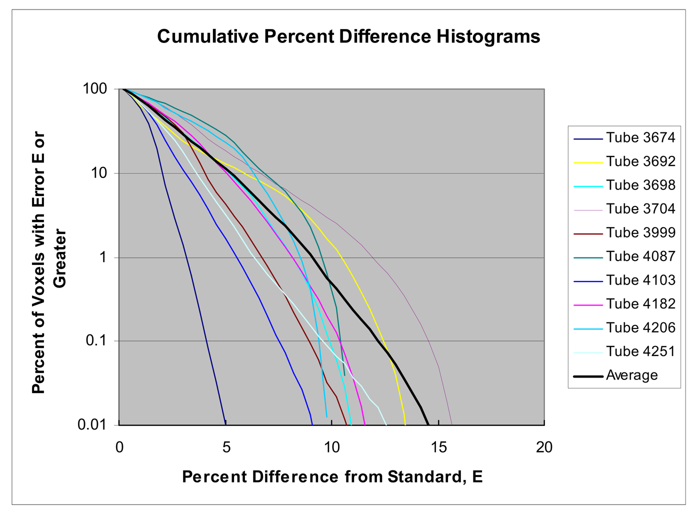

Figure 11. Error volume histograms for ten sources and their average.

SUMMARY

Dose measurements were made for 20 sources at spatial points surrounding the Xoft Axxent™ X-ray Source to determine anisotropy, azimuthal dependence and depth-dose. From these points, a full volumetric data set was created for each source individually, and for the overall average to create a reference standard. Point by point comparisons of each source to the standard were made in terms of absolute dose difference in Gy, and in percent terms. For treatment planning purposes these can be considered as dose errors. Visualization techniques are used to examine patterns of the absolute dose and dose differences. Histograms of dose and dose differences show the frequency distribution of errors on a per-source basis and as an average.

CONCLUSIONS

Using spatial dose data acquired for multiple Xoft Axxent™ HDR X-ray Sources, volumetric data sets were constructed by interpolation and fitting. Data sets for individual sources were compared voxel by voxel to the average of 20 sources. Dosimetric "errors" were then studied by means of data visualization techniques and "Error Volume Histograms". For the average source, 90% of voxels have an error less than 5.4%, and 99% have an error less than 9%.

Study Funded by Xoft