QUANTITATIVE ASSESSMENT OF INTERSTITIAL IMPLANTS

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Quantitative assessment of interstitial implants is proposed using volume versus dose curves and four well-defined dosimetric parameters. The volume versus dose curves, both differential and cumulative, provide quantitative data on the volumes of tissues irradiated to different doses. They also offer a qualitative assessment of the variations in dose delivery. The dose nonuniformity ratio (DNR) quantitatively determines the degree of dose nonuniformity specific to the implant configuration. The dose rate at which the DNR shows a minimum value, if selected as the treatment dose rate, gives an optimized dose distribution. The three volumetric irradiation indices are formulated with respect to a well-defined target volume. They offer quantitative data on the extent to which the implant delivers the prescribed dose to the target volume. These dosimetric parameters determine the degree of coverage of the target volume, dose homogeneity within the target volume, and irradiation of tissues outside the target volume. The method of quantitative assessment is demonstrated using, as examples, an ideal Ir-192 double-plane implant and an actual clinical Ir-192 double-plane breast implant.

Brachytherapy, Interstitial implants, Dosimetry, Dose uniformity

INTRODUCTION

Over the years, several dosimetry systems have been developed for interstitial brachytherapy (2, 4–6, 8, 10, 15). The rules of implantation, the geometrical distribution of the radioactive sources, and the source strength specifications to achieve a certain dose distribution pattern are unique to each dosimetry system. Hence the implant configuration, the distribution of source activity, and the choice of treatment dose rate vary among the systems. These variations arise from philosophical differences in the approach of performing interstitial implants. As a consequence of these variations, the size and shape of the treatment volume also differ from one dosimetry system to another. In addition, the actual clinical implants are rarely identical to the planned ideal implants, thus exhibiting deviations from the intended dose distribution pattern and dose delivery. Any attempt to correlate and compare clinical results will require calculation and documentation of the 3-dimensional dose distribution patterns achieved from the clinical implants.

Currently, the generation of dose distribution patterns from interstitial implants is being routinely performed using computers. With the availability of high speed computers, time is no longer a factor when one considers the calculation of the doses to a large number of volume elements. The calculated doses are usually presented as isodose lines in several planes. The radiation oncologist uses these spatial dose distribution patterns together with relevant clinical data, such as the extent and location of the tumor and target volume, to select the treatment volume and treatment dose rate. This qualitative assessment often results in large variations of dose delivered both within and outside the target volume. The lack of appropriate dosimetric parameters to quantify and characterize the dose distribution patterns from interstitial implants has made the evaluation and comparison of clinical outcomes difficult.

In recent years, attempts have been made to assess interstitial implants quantitatively (1, 3, 7, 9, 11–14). Volume versus dose curves have been used to assess interstitial implants. The uniformity of the implant has been evaluated quantitatively by the dose homogeneity index (14), uniformity index (9), ratio of two volumes (7), and the width of enhancement in a modified volume versus dose curve (2). However, the specific dosimetric characteristics of the interstitial implants that are of clinical importance have not been clearly defined. We have been investigating

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some clinical criteria such as adequacy of the coverage of the target volume, uniformity of the dose delivery within the target volume, and tissues being irradiated outside the target volume (11, 12). This paper presents a study of the characteristics of the volume versus dose distributions and the use of well-defined quantitative parameters to assess the quality of interstitial implants.

METHODS AND MATERIALS

A double-plane interstitial implant was chosen as an example for this study. The implant was configured using uniform linear activity sources arranged in parallel. Both the linear source spacing and plane spacing were 1.5 cm. The target volume has the dimensions of 8 cm × 8 cm × 2.5 cm. Three-dimensional dose distribution patterns and the differential volume versus dose rate curve were generated for this implant by computing the dose at volume elements of 1.0 mm × 1.0 mm × 1.0 mm spaced 1.0 mm apart. Doses were computed in 3-dimensional space extending 3.0 cm beyond the edge of the target volume. The cumulative volume versus dose rate curve was generated by integrating the volume elements receiving dose rates equal to or greater than a reference dose rate.

Four quantitative parameters were determined for the double-plane implant. The dose nonuniformity ratio (DNR) is defined as the ratio of the high dose volume to the reference volume (12). The high dose volume refers to the volume receiving dose rates equal to or greater than a multiplicative factor (≥1.0) of the reference dose rate. The reference volume is the volume that receives dose rates equal to or greater than the reference dose rate. A multiplicative factor of 1.5 suggested by Saw et al. (11) was used in this study. The DNR was determined for reference dose rates varying from 10 cGy/hr to 90 cGy/hr in steps of 2 cGy/hr. The other three dosimetric parameters are volumetric irradiation indices which are based on a knowledge of the location and the extent of the target volume (11). The coverage (CI) index is a measure of the fraction of the target volume receiving dose rates equal to or greater than the reference dose rate. The external volume (EI) index quantitates the amount of tissue external to the target volume, expressed as a percentage of the target volume, that receives dose rates equal to or greater than the reference dose rate. The relative dose homogeneity (HI) index measures the fraction of the target volume receiving dose rates in the range of 1.0–1.5 times the reference dose rate. The irradiation indices were determined for reference dose rates varying from 20 cGy/hr to 80 cGy/hr in steps of 2 cGy/hr.

To demonstrate the application of these parameters to assess quantitatively the clinical adequacy of an implant, a typical double-plane breast implant is presented. The clinical implant was performed to irradiate the tumor bed and surgically manipulated tissues following lumpectomy in the management of a breast malignancy. The double-plane implant was configured using Ir-192 sources consisting of seeds spaced 0.5 cm apart.

RESULTS

The differential volume versus dose rate curve for the idealized double-plane implant is shown in Figure 1. A few general features can be identified in this curve. The volume increases as the dose rate decreases. The volume receiving high dose rates is small. The asymptotic behavior of the curve is as expected based on the physics of the dose rate distributions from radioactive sources. Superimposed onto the smooth volume distribution is a peak. The peak indicates that a large volume is receiving a narrow range of dose rates. The magnitude and full-width-half-maximum (FWHM) of the peak are determined by the configuration of the implant. For a poorly configured implant, the magnitude of the peak would be small with a broad FWHM. On the other hand, for an implant that produces a uniform dose rate distribution, the magnitude will be large with a narrow width peak.

The cumulative volume versus dose rate curve for this double-plane implant is shown in Figure 2. As expected, the cumulative volume decreases with increase in the dose rate. The curve should exhibit a change in slope at the dose rate where the peak is present on the differential volume versus dose rate curve. The curve will exhibit a discontinuity at this particular dose rate if the implant results in a homogeneous dose distribution. The shape of the fall-off and the closeness to resembling a step function may be useful indicators of dose uniformity within the treatment volume. However, as seen in the figure, the slope change is not clearly evident for this implant. The lack of a distinct fall-off diminishes its application in the assessment of dose uniformity. However, the cumulative volume versus dose rate plot allows a direct extraction of the treatment volume for any chosen treatment dose rate.

Fig. 1. Differential volume versus dose rate curve for a double-plane interstitial implant.
The DNR for the double-plane implant is shown in Figure 3. The DNR has a constant value at low reference dose rates, then decreases to a minimum value and increases at higher reference dose rates. The occurrence of a minimum in the DNR indicates that for a specific implant configuration, there is a reference dose rate which, if chosen as the treatment dose rate, will produce an optimally uniform dose distribution. In the ideal case where the dose distribution is uniform, the DNR will be zero. However, in clinical implants the DNR will be always greater than zero, presenting the existence of high dose regions in particular surrounding each source. The clinical objective is to minimize the DNR value by appropriately designing the implant. In addition to obtaining the dose rate at which the DNR is minimum, the DNR also explicitly measures the degree of dose nonuniformity for other choices of treatment dose rates.

The variation of the three volumetric irradiation indices as a function of the reference dose rate is shown in Figure 4. The coverage of the target volume decreases as the reference dose rate increases. Correspondingly, the volume of tissue outside the target volume that is irradiated to doses higher than the reference dose also decreases. These factors are quantitatively measured by the CI and EI indices, respectively, as shown in the figure. The HI index exhibits a maximum peak value, implying that the dose homogeneity within the target volume is optimized at this particular reference dose rate. In the ideal implant, one expects to have complete coverage of the target volume with a homogeneous dose distribution and with no tissues outside the target volume receiving doses exceeding the treatment dose. Such an ideal implant will have both CI and HI indices equal to 100% and the EI index as zero at a particular treatment dose rate. However, the physical characteristics of interstitial implants are such that it is not possible to achieve this ideal condition.

Isodose rate distributions in the central plane, that is, the plane orthogonal to and bisecting the implant planes, and in the plane orthogonal to this central plane are shown in Figure 5. The isodose rate line of 40 cGy/hr is the dose rate at which the HI index is optimized. The other isodose lines are for dose rates either 0.50, 1.25, or 1.50 times this particular dose rate. These isodose rate distributions provide the spatial information of delivered doses. Both the spatial and volumetric data are essential to describe completely the quality of the interstitial implants.

DISCUSSION

An important clinical objective in radiation therapy is to deliver a uniform dose covering the entire target volume and to spare the surrounding normal tissue. The very nature of the brachytherapy method of delivering the required dose, where the radiation sources are implanted within the target volume, makes it difficult to achieve these desired goals successfully. Interstitial implants do exhibit large dose variations across the irradiated volume with
tissues in close proximity to the sources and in the central region of the implant, receiving high doses. A knowledge of the size and extent of the high dose regions would be useful in correlating any observed complications associated with high doses, such as necrosis. Volume versus dose curves shown in Figures 1 and 2 provide a quantitative description of the dose distributions. The variations of doses can be qualitatively assessed based on these curves. However, these curves do not provide any physical parameters that can be associated with clinical outcome. The DNR values, which are the high dose volumes expressed as a fraction of the treatment volume, allow a quantitative assessment of the implant configuration. Optimal dose uniformity is achieved for a defined implant arrangement if the treatment dose rate selected is that dose rate for which the DNR is a minimum. If a different value is selected as the treatment dose rate, then the degree of dose nonuniformity can be directly extracted from the DNR plots. The DNR plots are a representation of the volumetric data specific to the implant configuration and are not influenced by the extent and location of the target volume.

Fig. 5. Isodose rate distributions in the central plane and a plane orthogonal to the central plane for the double-plane implant. Labeled are isodose rates expressed in cGy/hr.

Any meaningful analysis of the clinical adequacy of an interstitial implant requires information on the extent and location of the target volume. These data are difficult to obtain in most clinical situations. At best, a reasonable
estimate is made from the various imaging procedures and relevant clinical information. If the target volume is well-defined, then the extent to which the implant delivers the desired treatment can be quantitatively assessed using the three volumetric irradiation indices. The quality of the implant certainly depends on the extent to which the target volume is enclosed by the treatment dose rate. The degree of the coverage, measured by CI index, may prove useful in correlating treatment failures. Another aspect of the quality of the implant depends on the irradiation of surrounding normal tissues. The EI index measures the extent to which these tissues are being irradiated. This index can be correlated to complications of treatment occurring outside the target volume. It is also of clinical importance to deliver the dose homogeneously across the target volume. The degree of dose homogeneity achieved by any implant is measured by the HI index. This index allows for possible correlation of complications arising inside the target volume. The obvious clinical objective is to maximize both the CI and HI indices and minimize the EI index. However, the three volumetric irradiation indices may not be optimized simultaneously at a particular reference dose rate. The significance placed on each of these indices will depend on the clinical intent of the particular implant treatment. Clinical judgment will have to be exercised in the final selection of the appropriate dose rate for treatment. The values of the three volumetric irradiation indices for the chosen treatment dose rate should provide a good quantitative description of any clinical implant. If the target volume assumes the contour of the treatment dose rate, then CI index is 100%, EI index is zero, and HI has the value of (100-DNR) %.

Figure 6 shows the DNR as a function of the reference dose rate for a clinical double-plane implant performed following lpectectomy in the management of a breast malignancy. The minimum value for the DNR occurs at a reference dose rate of 54 cGy/hr. This particular reference dose rate was chosen as the treatment dose rate after the physician was satisfied that this isodose contour adequately encloses the target volume. The distribution of isodose rate lines in two orthogonal planes are shown in Figure 7. The concentration of the high dose volume is shaded to represent pictorially the dose non-uniformity. If the physician had expressed concern over the coverage of the target volume, the choice for the treatment dose rate would be a lower value. In such a case, a compromise would have been made with respect to the dose uniformity. If the target volume is documented ahead of the treatment, then the irradiation indices can be calculated and used effectively in the decision-making process of prescription. These quantitative parameters, together with the dimensions of the treatment volume in three orthogonal planes, provide useful information for proper documentation and reporting of the implant.

CONCLUSION

Interstitial implants can be quantitatively assessed using dosimetric parameters such as the DNR and the volumetric irradiation indices. These parameters are based on volumetric data and have simple physical and clinical interpretations. These parameters can be easily calculated for use in pre- and post-implant assessment. The DNR value can be used to report the high dose volume directly. The three volumetric irradiation indices can be used to report the underdosage to the target volume, the overdosage to the surrounding tissues, and dose homogeneity within the target volume. These parameters provide clinically relevant quantitative data that are useful in selecting the dose rate for treatment as well as correlating the treatment to clinical outcome.

REFERENCES