A nomogram to determine required seed air kerma strength in planar $^{131}$Cesium permanent seed implant brachytherapy

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Abstract

**Purpose:** Intraoperatively implanted Cesium-131 ($^{131}$Cs) permanent seed brachytherapy is used to deliver highly localized re-irradiation in recurrent head and neck cancers. A single planar implant of uniform air kerma strength (AKS) seeds and 10 mm seed-to-seed spacing is used to deliver the prescribed dose to a point 5 mm or 10 mm perpendicular to the center of the implant plane. Nomogram tables to quickly determine the required AKS for rectangular and irregularly shaped implants were created and dosimetrically verified. By eliminating the need for a full treatment planning system plan, nomogram tables allow for fast dose calculation for intraoperative re-planning and for a second check method.

**Material and methods:** TG-43U1 recommended parameters were used to create a point-source model in MATLAB. The dose delivered to the prescription point from a single 1 U seed at each possible location in the implant plane was calculated. Implant tables were verified using an independent seed model in MIM Symphony LDR™. Implant tables were used to retrospectively determine seed AKS for previous cases: three rectangular and three irregular.

**Results:** For rectangular implants, the percent difference between required seed AKS calculated using MATLAB and MIM was at most 0.6%. For irregular implants, the percent difference between MATLAB and MIM calculations for individual seed locations was within 1.5% with outliers of less than 3.1% at two distal locations (10.6 cm and 8.8 cm), which have minimal dose contribution to the prescription point. The retrospectively determined AKS for patient implants using nomogram tables agreed with previous calculations within 5% for all six cases.

**Conclusions:** Nomogram tables were created to determine required AKS per seed for planar uniform AKS $^{131}$Cs implants. Comparison with the treatment planning system confirms dosimetric accuracy that is acceptable for use as a second check or for dose calculation in cases of intraoperative re-planning.

**Key words:** brachytherapy, Cesium-131, intraoperative brachytherapy, permanent seed implant, head and neck cancer, nomogram.
determined using Monte Carlo simulations, radiochromic film, and thermoluminescent dosimetry measurements [1,14,15,16,17,18,19].

At our institution, $^{131}$Cs implants following historical planar implant techniques are performed for resectable recurrent head and neck cancers at the time of surgical intervention. Treatment planning is typically done prior to surgery with a sophisticated brachytherapy treatment planning system (TPS), however, sometimes the treatment plan is changed during surgery due to intraoperative findings. In these cases, a nomogram can be used by the physicist to provide an estimate of the adjusted implant dose. Additionally, a nomogram can be used as a secondary check of the treatment plan created with the brachytherapy dose calculation system for all cases. Unlike other radionuclides, $^{131}$Cs was first used in PSI well after sophisticated TPS were standard in clinics, so standard implant tables have not been published [20,21,22].

In this work, nomograms for efficient and simple point dose calculation of rectangular and irregular planar implants prescribed to a point 5 mm or 10 mm away from an implant plane are presented. The prescription dose is not defined, and nomogram tables may be used for any prescribed dose.

**Material and methods**

**Clinical treatment planning and prescription**

Cesium-131, Proxcelan Model CS-1 Rev2 (Isoray Medical, Richmond, WA) (Figure 1) implants are used to provide highly localized re-irradiation in recurrent head and neck patients at the time of salvage surgery. Source placement follows historical planar implant techniques. Uniform strength seeds for PSI are ordered pre-loaded in individual strands or in a mesh. Seeds are stranded 10 mm apart, with the intent to implant individual strands 10 mm apart. If a mesh is ordered, seeds are sewn into the mesh in a 10 mm by 10 mm grid pattern. The number of seeds required for an implant is determined in collaboration with the radiation oncologist and surgeon. Seeds are manually placed in a grid pattern, and the prescription point is identified and delineated. The seed AKS is iteratively adjusted such that the prescription dose is delivered to the prescribed depth. This planning process requires coordination between the medical physicist, radiation oncologist, and surgeon, and can take a few hours from scan import, physician(s) contouring, and physicist planning to final physician(s) approval. Treatment planning using a nomogram can be done in minutes based on physician described implant dimensions rather than import and contouring of 3D volume imaging.

**Rectangular implant tables**

Calculations for rectangular implant tables were performed using MATLAB (Mathworks®, Natick, MA). The $^{131}$Cs (Rev 2) point source and line source seed model data, as per the American Association of Physicists in Medicine’s TG-43 equation [23] (dose-rate constant, radial dose function, and 1D/2D anisotropy functions [17]) were input into MATLAB. Linear interpolation between each data point was used. The dose-rate at a prescription point 5 mm or 10 mm away from the implant plane was calculated for rectangular arrays of 1 U seeds placed 10 mm apart in a grid pattern ranging from $1 \times 1$ up to $16 \times 16$ seeds. The total dose delivered by a single seed $n$ was calculated by integrating the dose-rate of that seed $D_{0,n}$ over the duration of the permanent implant.

\[
D_n = \int_0^\infty D_{0,n} \frac{1}{2} \frac{1}{T} \frac{1}{t} \, dt
\]

The total dose delivered to the prescription point over the lifetime of the implant was calculated by summing the contribution from each seed $n$ in an implant of $N$ seeds:

\[
D_{total} = \sum_{n=1}^N \int_0^\infty D_{0,n} \frac{1}{2} \frac{1}{T} \frac{1}{t} \, dt = \frac{T_{1/2}}{m^2} \sum_{n=1}^N D_{0,n}
\]
Irregular implants

To determine the dose delivered by a non-rectangular planar implant, the dose rate at the 5 mm and 10 mm prescription points from a single 1 U seed at each possible location in the 16 × 16 cm² grid was calculated in MATLAB using the methods described above for regular implants. This was done using the 1D and 2D formalisms.

Verification of implant tables using MIM Symphony LDR

Verification of the implant tables was performed in MIM Symphony LDR™ for the 1D and 2D formalisms. The point source seed model data were input into MIM during previous commissioning [24]. Seeds were placed at a distance of 10 mm center-to-center in a single planar arrangement. The total dose delivered by a 1 U seed was recorded for each possible seed position in the 16 × 16 cm² grid to verify the irregular implant tables, and the total dose from an array of seeds was recorded to verify the rectangular implant tables. These values were compared to those calculated in MATLAB.

Application to patient implants

Nomogram tables were used retrospectively to determine the required seed AKS for the three most recent rectangular and three most recent irregular clinical implant cases. All six implants were prescribed 60 Gy to a point 5 mm from the implant plane. The implant geometry and prescription point for each patient are shown in Figure 2.

For the rectangular plans, the dose rate in the implant table represents a rectangular arrangement of 1 U seeds. The desired AKS is calculated using the following equation:

\[
\text{Required AKS} = \frac{\text{Prescription dose}}{\text{Dose delivered to prescription point by 1 U seeds}}
\]

For irregular seed arrangements, the desired AKS per seed is obtained by dividing the prescription dose by the sum of the total dose delivered to the prescription point by each seed in the implant:

\[
\text{Required AKS} = \frac{\text{Prescription dose}}{\sum \text{Dose delivered to prescription point by seed } n}
\]

The required AKS calculated by the implant tables and by MIM were recorded.

Results

Rectangular implant tables

The total dose delivered to 5 mm and 10 mm prescription points by a planar array of 1 U seeds calculated in MATLAB are presented in Table 1 (1D formalism) and Table 2 (2D formalism). Using the 1D formalism, all differences in required AKS between MATLAB and MIM were less than 0.6%. Using the 2D formalism, all differences were less than 1.4%.

Irregular tables

The dose delivered over the lifetime of an implant by a 1 U seed at each location in an implant to prescription points located 5 mm and 10 mm perpendicular to the center of the implant plane are presented in Table 3 using the 1D and 2D formalisms. The numbering along the table edges are used to represent the seed indexing number, and not a distance from the prescription point. To highlight differences between the two dose calculation formalisms, bolded values indicate a difference between line and point source models that are greater than 5% for a single seed’s contribution to the prescription point; bolded and underlined values indicate greater than 10%, with a maximum of 16.9%.

Application to patient plans

The required AKS per seed was determined clinically using MIM and then retrospectively using the implant tables for the three most recent rectangular and three most recent irregular implants. The seed AKS calculated using MIM and implant tables are presented in Table 4. For all six patient plans, the percent difference was less than 3%.

Discussion

The nomogram tables created with MATLAB show good agreement with those calculated using MIM (maximum difference of 3.0%). For seeds very close to the pre-
Table 1. The total dose delivered (in Gy) to the prescription points (A) 5 mm and (B) 10 mm perpendicular to the implant plane by a rectangular array of \(x\) by \(y\) 1 U seeds, calculated using the 1D formalism in MATLAB. All implant arrangements prescribed to 5 and 10 mm have differences between the MIM and MATLAB calculations of less than 0.4%, and 0.6%, respectively.

|   | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   | 13   | 14   | 15   | 16   |
|---|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| A |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| y |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 1 | 4.60 | 9.19 | 10.37| 11.55| 11.97| 12.40| 12.87| 13.02| 13.10| 13.13| 13.15| 13.17|      |      |      |      |
| 2 | 18.38| 20.74| 23.10| 23.95| 24.80| 25.18| 25.56| 25.75| 25.94| 26.04| 26.15| 26.20| 26.26| 26.26| 26.30| 26.33|
| 3 | 23.74| 26.75| 27.90| 29.06| 29.59| 30.13| 30.40| 30.68| 30.83| 30.98| 31.06| 31.15| 31.20| 31.25|      |      |
| 4 | 30.39| 31.86| 33.32| 34.01| 34.70| 35.06| 35.42| 35.81| 35.92| 36.04| 36.10| 36.17|      |      |      |      |
| 5 | 33.51| 35.16| 35.97| 36.77| 37.19| 37.61| 37.85| 38.08| 38.22| 38.35| 38.44| 38.52|      |      |      |      |
| 6 | 37.01| 37.92| 38.83| 39.32| 39.81| 40.08| 40.51| 40.87| 41.06| 41.17| 41.29| 41.42|      |      |      |      |
|    | 38.91| 39.89| 40.42| 40.96| 41.26| 41.56| 41.74| 41.92| 42.03| 42.13|      |      |      |      |      |      |
|    | 40.95| 41.53| 42.11| 42.44| 42.77| 42.97| 43.17| 43.29| 43.41|      |      |      |      |      |      |      |
| B |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| y |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 1 | 2.25 | 4.50 | 5.40 | 6.31 | 6.68 | 7.06 | 7.23 | 7.41 | 7.50 | 7.59 | 7.64 | 7.69 | 7.72 | 7.74 | 7.76 | 7.78 |
| 2 | 8.99 | 10.81| 12.62| 13.37| 14.11| 14.46| 14.81| 15.00| 15.18| 15.28| 15.38| 15.43| 15.49| 15.52| 15.56|      |
| 3 | 13.16| 15.51| 16.54| 17.56| 18.06| 18.55| 18.81| 19.07| 19.22| 19.36| 19.45| 19.53| 19.58| 19.63|      |      |
| 4 | 18.40| 19.71| 21.01| 21.65| 22.29| 22.63| 22.97| 23.16| 23.35| 23.46| 23.57| 23.64| 23.70|      |      |      |
| 5 | 21.19| 22.66| 23.41| 24.16| 24.56| 24.96| 25.39| 25.54| 25.56| 25.68| 25.76| 25.83|      |      |      |      |
| 6 | 24.32| 25.17| 26.02| 26.48| 26.95| 27.21| 27.47| 27.63| 27.88| 27.97|      |      |      |      |      |      |
| 7 | 26.09| 27.01| 27.52| 28.03| 28.32| 28.61| 28.78| 28.96| 29.06| 29.16|      |      |      |      |      |      |
| 8 | 28.00| 28.55| 29.11| 29.43| 29.75| 29.94| 30.13| 30.25| 30.36|      |      |      |      |      |      |      |
| 9 | 29.14| 29.72| 30.06| 30.40| 30.61| 30.81| 30.94| 31.06| 31.17|      |      |      |      |      |      |      |
| 10| 30.34| 30.70| 31.06| 31.28| 31.50| 31.63| 31.77|      |      |      |      |      |      |      |      |      |
| 11| 31.08| 31.45| 31.68| 31.91| 32.05| 32.19| 32.22|      |      |      |      |      |      |      |      |      |
| 12| 31.84| 32.08| 32.32| 32.47| 32.62|      |      |      |      |      |      |      |      |      |      |      |
| 13| 32.33| 32.58| 32.73| 32.88|      |      |      |      |      |      |      |      |      |      |      |      |
| 14| 32.83| 32.99| 33.15| 33.32|      |      |      |      |      |      |      |      |      |      |      |      |
| 15|      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 16|      |      |      |      |      |      |      |      |      |      |      |      |      |      |      | 33.48 |
Table 2. The total dose delivered (in Gy) to the prescription points (A) 5 mm and (B) 10 mm perpendicular to the implant plane by a rectangular array of z by r 1 U seeds, calculated using the 2D formalism in MATLAB, where z and r are the number of seeds along the seeds' long and short directions, respectively.

| z | r | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|
| 1 | 2.33 | 3.45 | 6.42 | 6.77 | 7.11 | 7.26 | 7.42 | 7.50 | 7.58 | 7.62 | 7.66 | 7.69 | 7.73 | 7.77 | 7.81 | 7.85 | 7.89 |
| 2 | 3.65 | 5.12 | 6.18 | 5.49 | 4.91 | 4.43 | 4.05 | 3.77 | 3.59 | 3.43 | 3.28 | 3.14 | 3.01 | 2.88 | 2.75 | 2.63 | 2.51 |
| 3 | 6.55 | 13.19 | 3.98 | 18.85 | 19.34 | 19.83 | 20.34 | 20.86 | 21.38 | 21.84 | 22.36 | 22.88 | 23.41 | 23.94 | 24.47 | 25.00 | 25.53 |
| 4 | 8.94 | 13.89 | 17.05 | 21.61 | 23.02 | 24.47 | 25.93 | 27.40 | 28.87 | 30.34 | 31.81 | 33.29 | 34.76 | 36.23 | 37.69 | 39.16 | 40.63 |
| 5 | 7.52 | 15.04 | 18.12 | 21.57 | 25.05 | 28.52 | 32.00 | 35.50 | 39.01 | 42.52 | 46.04 | 49.57 | 53.10 | 56.64 | 60.18 | 63.72 | 67.27 |
| 6 | 7.70 | 15.41 | 18.64 | 22.24 | 25.93 | 29.62 | 33.32 | 37.04 | 40.77 | 44.53 | 48.32 | 52.15 | 56.00 | 59.85 | 63.70 | 67.55 | 71.40 |
| 7 | 7.80 | 15.70 | 18.93 | 22.37 | 26.06 | 29.77 | 33.49 | 37.23 | 40.97 | 44.74 | 48.55 | 52.36 | 56.19 | 60.03 | 63.87 | 67.71 | 71.56 |
| 8 | 7.90 | 15.97 | 19.20 | 22.62 | 26.30 | 29.92 | 33.65 | 37.39 | 41.13 | 44.89 | 48.67 | 52.46 | 56.25 | 60.01 | 63.87 | 67.72 | 71.57 |
| 9 | 8.00 | 16.07 | 19.43 | 22.87 | 26.55 | 30.18 | 33.92 | 37.66 | 41.39 | 45.15 | 48.92 | 52.70 | 56.47 | 60.23 | 63.99 | 67.75 | 71.60 |
| 10 | 8.10 | 16.16 | 19.66 | 23.10 | 26.84 | 30.47 | 34.22 | 37.96 | 41.69 | 45.45 | 49.22 | 53.00 | 56.76 | 60.52 | 64.28 | 68.04 | 71.80 |
| 11 | 8.20 | 16.25 | 19.89 | 23.34 | 27.03 | 30.70 | 34.45 | 38.19 | 41.93 | 45.69 | 49.46 | 53.24 | 56.99 | 60.75 | 64.51 | 68.27 | 72.03 |
| 12 | 8.30 | 16.34 | 20.12 | 23.58 | 27.34 | 30.97 | 34.71 | 38.45 | 42.19 | 45.95 | 49.72 | 53.49 | 57.24 | 60.99 | 64.75 | 68.51 | 72.27 |
| 13 | 8.40 | 16.43 | 20.36 | 23.82 | 27.60 | 31.20 | 34.96 | 38.70 | 42.44 | 46.20 | 49.97 | 53.74 | 57.49 | 61.24 | 65.00 | 68.76 | 72.52 |
| 14 | 8.50 | 16.52 | 20.59 | 24.06 | 27.86 | 31.45 | 35.21 | 39.05 | 42.79 | 46.55 | 50.31 | 54.07 | 57.82 | 61.57 | 65.33 | 69.09 | 72.85 |
| 15 | 8.60 | 16.61 | 20.83 | 24.30 | 28.12 | 31.70 | 35.47 | 39.30 | 43.04 | 46.80 | 50.56 | 54.32 | 58.07 | 61.83 | 65.59 | 69.35 | 73.11 |
| 16 | 8.70 | 16.70 | 21.06 | 24.54 | 28.38 | 31.96 | 35.73 | 39.54 | 43.28 | 47.04 | 50.80 | 54.56 | 58.31 | 62.07 | 65.83 | 69.59 | 73.35 |
Table 3. Total dose delivered (in Gy) to the 5 mm and 10 mm prescription points by each 1 U seed in an irregular implant, using the point and line source models. Each quadrant can be mirrored about the prescription point to create a full table. Bolded values indicate a difference between line and point source models that are greater than 5% for a single seed’s contribution to the prescription point; bolded and underlined values indicate greater than 10%, with a maximum of 16.9%.

| r   | z   | Point source model | Line source model |
|-----|-----|--------------------|-------------------|
| 8   | 8   | 0.005              | 0.005             |
| 7   | 6   | 0.007              | 0.007             |
| 6   | 5   | 0.009              | 0.009             |
| 5   | 4   | 0.012              | 0.012             |
| 4   | 3   | 0.014              | 0.014             |
| 3   | 2   | 0.017              | 0.017             |
| 2   | 1   | 0.021              | 0.021             |
| 1   | 0.024 | 0.024              | 0.024             |
| 5 mm| 0.027 | 0.027              | 0.027             |
| 10 mm| 0.030 | 0.030              | 0.030             |
| 8   | 0.034 | 0.034              | 0.034             |
| 7   | 0.037 | 0.037              | 0.037             |
| 6   | 0.040 | 0.040              | 0.040             |
| 5   | 0.043 | 0.043              | 0.043             |
| 4   | 0.046 | 0.046              | 0.046             |
| 3   | 0.049 | 0.049              | 0.049             |
| 2   | 0.052 | 0.052              | 0.052             |
| 1   | 0.055 | 0.055              | 0.055             |
Cs-131 air kerma strength nomogram

Table 4. The rectangular and irregular implant tables are used to determine AKS (in U) for the three most recent rectangular and irregular patient plans. The percent difference in seed strengths determined using the two methods is presented for each case.

| Patient | Seed arrangement | Number of seeds | Tables | MIM Symphony | % difference |
|---------|------------------|-----------------|--------|--------------|--------------|
| 1       | Rectangle: 5 x 4 | 20              | 1.88   | 1.88         | 1.9          | 1.9          | −1.1%        | −1.1%        |
| 2       | Rectangle: 3 x 3 | 9               | 2.53   | 2.50         | 2.5          | 2.5          | 1.2%         | 0.0%         |
| 3       | Rectangle: 6 x 7 | 42              | 1.58   | 1.59         | 1.6          | 1.6          | −1.3%        | −0.6%        |
| 4       | Irregular: 5, 5, 3 | 13              | 2.23   | 2.23         | 2.3          | 2.2          | −3.0%        | 1.4%         |
| 5       | Irregular: 6, 6, 5, 4 | 21              | 1.88   | 1.86         | 1.9          | 1.9          | −1.1%        | −2.1%        |
| 6       | Irregular: 4, 7, 8, 8, 4, 2 | 33              | 1.67   | 1.67         | 1.7          | 1.7          | −1.8%        | −1.8%        |

Although treatment planning and seed ordering are performed during a preoperative CT planning session using sophisticated treatment planning software, the final dose is modified intraoperatively to fit the surgical defect in 10-20% of cases. Intraoperative considerations that can lead to these alterations include: location and exposure of the carotid artery within the operative field, bony anatomy that causes contour alterations, free flap reconstruction, and unexpected changes in the area of greatest concern for recurrence. Nomogram tables are used in the operating room to provide the surgeon and radiation oncologist an accurate dose estimate based on a number of seeds that differs from the preoperative planning session. A second check of the pre-planning dose is performed for all cases.

Unlike other permanent seed implant radionuclides, $^{131}$Cs was not used clinically until brachytherapy TPS were common in radiation therapy departments. Because of this, historical implant systems and data tables do not exist. The uniform seed strength and uniform seed spacing reported here is reminiscent of the Quimby system [25]. However, the choice of a prescription point that is not directly above a seed means that the prescription dose is the minimum dose in the central region of the 5 mm or 10 mm prescription point plane. The Manchester [26] and Quimby systems are prescribed such that the prescription dose is the modal or maximum dose in the treatment plane, respectively. The system of implant dosimetry reported here would therefore deliver more dose than an implant prescribed using the Manchester or Quimby conventions.

Conclusions

Nomogram tables to determine AKS per seed for rectangular and irregular planar $^{131}$Cs implants prescribed to 5 mm and 10 mm from the implant plane are presented. The nomogram tables may be adapted to any prescription dose. Tables were verified against MIM Symphony LDR™ planning system, including previous patient plans and yield seed activity calculations within clinically acceptable accuracy. These nomogram tables reduce time required for treatment planning or independent verification of a treatment plan. They also facilitate treatment planning in the operating room when patient anatomy requires an implant to deviate from the treatment plan.

Disclosure

Authors report no conflict of interest.

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