A Comparison Between Traditional and Continuous Delivery Methodologies for the Gamma Knife Perfexion

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Purpose

By utilizing multiple shots in Gamma Knife radiosurgery, one can improve the dose distribution.1 Currently for a multiple shot treatment plan, a single shot is delivered and the radiation is suspended while transitioning to the next shot. If a high number of shots are intended to be delivered, then the transitioning time in between shots can add to the overall treatment time. The purpose of this study is to investigate the differences between a traditional delivery method versus continuous delivery where the radiation is not suspend while transitioning to the next shot.

Introduction

Traditional Gamma Knife radiosurgery can be described as a knapsack problem that utilizes different collimator arrangements and shot positions.2 These different collimator arrangements and shot positions can be used to shape the isodose distribution to conform to the tumor volume. Current methods typically rely on the experience of the treatment planner for the selection of these different collimator arrangements and shot positions. This manual planning process can be tedious and as a result a suboptimal plan is often developed.

In 2007, Xiaoping Hu proposed using an inverse planning technique to arrive at a more optimal dose distribution. This new planning technique also proposed the use of a continuous delivery.3 A traditional plan is delivered in a series of steps that include moving to the planned position, opening the collimators, dwell for a specified duration, close the collimators, and move to the next planned positions. This traditional delivery relies on the suspension of the radiation during the transitions between all planned shot positions. The continuous delivery method tries to minimize the suspension of the radiation during the transition between shot positions. In 2009, a similar publication was now terming this continuous delivery as dynamic gamma knife radiosurgery and can also be called a “dose painting technique”. This new publication was geared to the utilization of the robotic trunions on the Gamma Knife C and robotic couch on the Perfexion.4

Since 2009, there have been several publications that have continued to investigate the continuous delivery method.5,6 These new publication primarily focus on the different optimization strategies and the resulting dose distribution from this new continuous delivery. The current literature is lacking in the direct comparison between traditional plans and dynamic plans. The aim of this project is to provide a quantitative analysis of the possible changes that can result when converting from a traditional delivery to a continuous delivery.

Methods

Several optimized plans were created for a single 4.3cc acoustic neuroma to deliver 12Gy to the 50% isodose line. Each plan was limited to the number of allowed shot positions: 5, 10, 15, 20, 25, 50, 100, and 200. Each plan was optimized for shot placement, collimator selection, and irradiation time for the Gamma Knife Perfection. To reduce the delivery time required the collimator settings were limited to only 16mm and 8mm for all 8 sectors. 4mm collimator settings and multi-collimator settings were not allowed in the optimization process. The optimized static delivery plans were then passed off to a custom program converting it into a continuous delivery.

The first step in this conversion process was to determine an optimal delivery path, which is based on the planned shot positions and collimator setting. The determination of the delivery path is fundamentally a traveling sales person problem.7 One of the approximate solutions to this problem is to use a nearest neighbor algorithm.8 This algorithm operates by picking a starting point, finding the next closest available point, and repeating the process until there are no more points. This algorithm does not find the absolute minimum, but it is able to find a local minimum in a relatively short amount of time. Since the nearest neighbor algorithm is starting point dependent, it was repeated for all possible starting points. This allowed the program to find a more optimal delivery path. For example, in the 25 shot plan the total path length was approximately 206mm for the unsorted path compared to 134mm for the sorted path. When assuming a couch speed of 6mm/second this can equate to about 12 seconds of reduction in the total treatment time. This algorithm was modified to limit the number of possible collimator changes. Only 2 collimator changes were allowed: 16mm -> 8mm and 8 -> 4mm.

The next step is to convert the delivery path into a continuous delivery path. Using the same custom program the delivery path was discretized to better simulate the continuous delivery. This process adds additional planned shot positions in between the original planned positions.

The final step is to calculate the resulting dose distributions. A TMR 10 based dose engine was developed from Elekta’s published data and validated with the clinical Leksell Gamma planning system9 The dose distributions for both delivery methods were calculated. Upon completion, the resulting dose distributions and delivery methods were compared. Beam on time, total treatment time, conformity, dose fall off, coverage, point analysis, and DVH analysis was performed for each plan.

Treatment Time Estimation

The collimator transition times were also measured to accurately calculate the total treatment time for the different delivery methods. A 16mm -> blocked or blocked -> 16mm collimator change was measured to take approximately 2.5 seconds each. Just like the 16mm, the collimator time for both 8mm and 4mm were both approximately 1.3 seconds each transition type. For the continuous delivery path the collimators will still transition to the blocked position when a collimator transition is required. For example, no collimator transition is required when traveling between two shot positions that have the same collimator setting. If the current shot has a collimator setting of 16mm and the next shot is 8mm, the collimator will transition into the blocked position during the travel phase between shots. To simulate the time required to travel between planned shot positions a couch speed of 6mm/second was assumed.

Continuous Delivery Conversion Process

The conversion from a traditional delivery to a continuous delivery was simulated by discretizing the travel path by adding additional shot positions. Figure 1 is shown to give a graphic representation and provide an example of the process outlined below.

The first step of this process is to calculate the distance between the original shot positions. This distance is now used to determine the number of segments that this path will be broken into. The number of segments is determined by a parameter that called dynamic step size, which in turn is the maximum segment size. The number of segments can be calculated using Equation 1

$$n = \left\lceil \frac{D}{DSS} \right\rceil \qquad \text{(Equation 1)}$$

where n is the number of segments, D is the distance between the two original shot positions, and DSS is the dynamic step size. Equation 2 can be used to determine the number of additional shots

$$\mathrm{N} = \mathrm{n} - 1 \qquad \text{(Equation 2)}$$

where N is the number of additional shots. The time associated with each additional shot is based on the time required to travel between the original shots and the number of segments. In order to calculate the travel time a couch speed of 6mm/second was assumed. Travel time can be calculated using Equation 3 and the time for each segment can be calculated using Equation 4. The time for each additional shot is equal to the time for each segment.

$$T = \frac{D}{6\ \frac{mm}{sec}} \qquad \text{(Equation 3)}$$

$$t = \frac{T}{n} \qquad \text{(Equation 4)}$$

where T is the travel time, and t is the segment time. To avoid excess added exposure time, the travel time was reduced evenly from the original two shot times. To account for the travel for the last remaining segment, half of this time is added back into the both of the original shot times. If this process ends up resulting in the original shot time being less than zero then the original shot time will be assigned a time of zero. Because of this approximation it is possible for the total beam on time to become greater for the continuous delivery compared to the traditional delivery. The new original shot time can be calculated using Equation 5

$$t_{n,new} = \begin{cases} 0, & t_n - \frac{T}{2} + \frac{t}{2} \le 0 \\ t_n - \frac{T}{2} + \frac{t}{2}, & t_n - \frac{T}{2} + \frac{t}{2} > 0 \end{cases} \qquad \text{(Equation 5)}$$

where tn,new is the modified original shot time, tn is the original shot time.

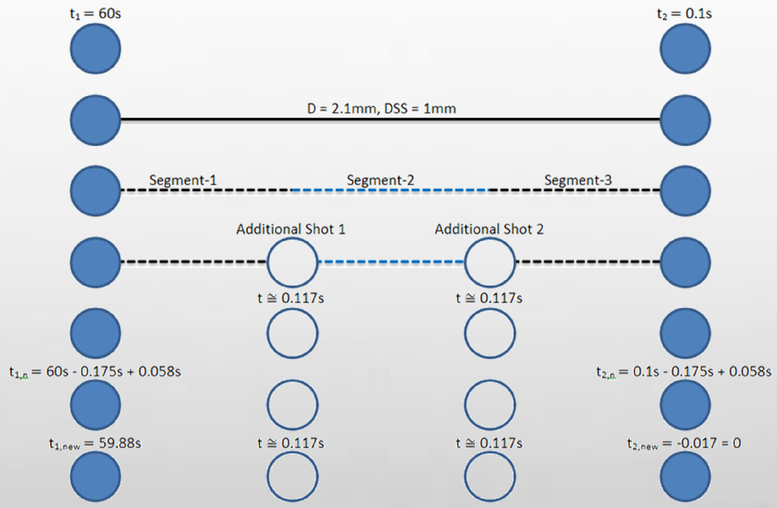

Figure 1 : Example continuous delivery conversion process, blue circles represent a traditional shot, white circles represent an additional shot that is added for the continuous delivery, D represents the travel distance, DSS represents the dynamic step size.

Results

Table 1 shows several different metrics that were used to quantify what changes might occur when converting from a traditional delivery to a continuous delivery. Ideally the traditional delivery will have the same exact beam on time as the continuous delivery but this will depends on the conversion process. In our conversion process it is possible for the continuous delivery to actually have a larger beam on time due the nature of how the time gets reallocated. This was explained in the previous section. It can also be seen that the total treatment time will decrease with the conversion between traditional delivery to continuous delivery since the radiation is not suspended in between shots. The -1.18% percent reduction in treatment time was for the 5 shot plan and corresponds to approximately 13 seconds. On the other side, the -23.23% corresponds to the 200 shot plan and the reduction in total treatment time was about 600 seconds. Using the Paddick’s definition for conformality from 2000 it can be seen that on average the conformality actually decreases during the conversion process. However, the opposite is true when using the 1999 ICRU definition for conformality. This relation is not necessarily contradicting since these definitions are different in one very important aspect and that is how the geographic location of the dose is used. Paddick’s definition relies on the overlap of the prescription dose and the target volume while the ICRU definition only looks at ratio of these two volume. Therefore, it is possible that the overlap between the prescription volume and target volume has decreased, but the ratio of these two volumes has actually increased. Looking at the 2006 definition for the gradient index from Paddick it can also be seen that on average the gradient index increases, which implies that the dose fall off is not as rapid for the continuous delivery compared to the traditional delivery. Lastly, on average the prescription coverage does increase for the continuous delivery compared to the traditional delivery. **Table 2** shows that across the board when converting from the traditional delivery to the continuous delivery the resulting dose distribution will become warmer. On average across all calculation points for all plans this increase corresponds to 0.12cGy to 1.2cGy or a maximum increase of 4.92cGy to 18.72cGy.

	Minimum	Mean	Maximum
Beam On Time	0.00%	0.04%	0.15%
Total Treatment Time	-23.23%	-6.52%	-1.18%
Paddick 2000 Conformity Index	-0.49%	-0.10%	0.09%
ICRU 1999 Conformity Index	-0.08%	0.21%	0.88%
Paddick 2006 Gradient Index	-0.09%	0.11%	0.55%
Prescription Coverage	-0.05%	0.06%	0.24%

Table 1: Percent change values between a continuous delivery vs. traditional delivery for all optimized plans (5-200 shots).

	Minimum	Mean	Maximum
Max Percent Change	0.54%	0.81%	1.32%
Mean Percent Change	0.04%	0.13%	0.35%
Max Rx Normalized Difference	0.41%	0.80%	1.56%
Mean Rx Normalized Difference	0.01%	0.04%	0.10%

Table 2: Point analysis between a continuous delivery vs. traditional delivery for all optimized plans (5-200 shots).

Conclusions

Transitioning to a continuous delivery methodology can decrease treatment time while providing a comparable dose distribution. Current data indicates that the continuous delivery methodology could allow for an increased number of shots. Previous studies have shown the dose distribution can be improved by delivering a high number of shots; therefore future studies will investigate increasing the number of shots.

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