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Radiation Oncology Treatment Using Optimization Techniques

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Abstract

Stereotactic radiosurgery is a three dimensional coordination that locates a target tumor detected in a diagnostic images with its actual location in the body and targeting the tumor for precise radiation surgery rather than excision with a blade. The research result presented here describes development of an optimization technique to replace conventional approach in radiation treatment. Precise radiation treatment is gaining popularity as an alternative to surgery in targeting tumors. The technique may apply to brain tumors following 3-D imaging and defining fixed reference points on the body multi-objective optimization problem to decide on the shot sizes, length, location, and the number of radiation shots. Beside the precision and accuracy of the technique speed of treatment in comparison with the conventional method is displayed. In conventional method this is achieved through an iterative approach.

Keywords: Stereotactic, Radiosurgery, Optimization, Skeletonization, Evolutionary Algorithm.

1. Introduction

Stereotactic radiosurgery SRS has gained popularity in replacing conversional surgery due to advances in medical imaging and computational techniques. This is mostly broadening its scope on treatment of certain disorders. The treatment is known as gamma knife technique. Types of disorders that malignant brain tumors, benign tumors within the head, malignant tumors from elsewhere in the body, vascular malformations, and functional disorders of the brain. The gamma knife delivers 201 beams from cobalt-60 radioactive sources through 201 holes in the protective hemisphere helmet. The focus of the radiation beams are in such a way that they intersect at the same location in the target area. Therefore, the area where all of the beams intersect is treated with a high dose of radiation. It is expected that the overall radiation has spherical dose distribution at the effective dose level. The treatment plan can be customized to treat lesions of varying sizes and shapes. Treatment typically consist of a number of shots of different sizes typically in the range of 4mm, 8mm, 14mm, and 18mm and shot duration, centered at different shot location in the tumor. Development of custom treatment plans for patients typically takes a considerable time, especially in the clinical phase. This is due to the amount of time it takes to engage in a trial-and-error process in an iterative approach to determine the ideal shot configuration to treat the patient in the most efficient and optimal time. The complexity and configuration of the target tumor can drastically increase the time required to plan and develop the treatment, given time is of the essence in such situations the sooner treatments can be developed the better the chances of eradicating the problem. Among the various approaches that have been considered for automation of multiple shots therapy for three dimensional radiosurgery is a shape treatment approach developed by Wu and Bourland (1996) [10].

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In this approach shape of the target tumor is focused on. Implementation of this technique is carried out using Skeletonization. This is a medial axis transformation, in which medical imaging is used to determine an ideal plan for treatment. Initially the skeleton is identified and emulated, before shot location and quantity of shots are determined. There are some variations in this approach and in some treatments number of shots is considered a variable parameter [10]. In this approach it increased variables by permitting the shot quantity, locations, sizes, and weights to vary rapidly based on shape and volume of targets.

Radiotherapy in general and Intensity-Modulated Radiotherapy IMRT in particular are treatment known to employ optimization algorithms. Bio-inspired Optimization techniques emulate processes in nature and provides search mechanism on a global area in order to reach optimal solutions [2]. Among these techniques Genetic Algorithm GA [1], [3], [9], exhaustive search techniques [5], [6], Simulated Annealing SA [7], [8] are well known solutions. The results reported have been promising and encouraging enough to continue to apply various search algorithms to this problem area. There are a number of parameters that need to be optimized. In IMRI planning, Genetic Algorithm has demonstrated promising success [4] in solving optimum solution for the beam angle.

The objective of this presentation is to plan optimum shot size and location by using Genetic Algorithm. This solution based on shot placement will allow the treatment team to design more effective and rapid treatment plan in comparison with the manual procedure and time consumption in its tuning and adjustments.

2. DEVELOPMENT OF OPTIMIZATION METHODOLOGY

A. Conditions pertinent to the treatment planning

Two objective functions are given primary consideration are shot location and size determination (SLSD) process in this Radiosurgery treatment planning. That is, the objective is to determine where to place shots and how large to make them initially. The process can be divided into two major phases. First, the skeleton (center line) is generated. Then, different number and size of shots are tried to place on the target along the skeleton. Radiosurgery treatment planning involves a number of physical limitations and medical uncertainties, for these reasons a number of assumption are made before a detailed process is developed:

- The tumor is represented by a 3D model.
- The target shape is moderate (between regular and irregular)
- The volume is limited, and dimensions do not exceed 35mm. The volume designed on a 3D grid of voxels in two subsets (in and out of the target)
- Outsize voxels are denoted by 0, inside voxel are denoted by 1.
- Four interchangeable outer collimator helmets with beam channel diameters w = {4, 8, 14, 18} mm which can irradiate different volumes.
- For a target volume larger than one shot, multiple shots can be used to cover the entire target. There is a boundary on the number of shots, typically it should be less than or equal to 15 shots.
- The dose cloud is perfectly spherical, or the overlap of radiation from the use of non-spherical shots can be negligible.

B. Development of a Three Dimensional Framework

The next step is the development of a replica 3D skeleton. Here the distance transformation/coding method is use to generate the replica 3D skeleton. The first step in skeleton generation is to compute the contour map containing distance information from the point to a nearest target boundary. The skeleton extraction method designed by Zhou, Kaufman and Toga [11] is used, based on the contour map. This method is used because it has demonstrated high accuracy and performance on medical images.

C. Location

Following development of 3-D framework know as skeleton the focus of attention is on the voxels and to determine the location for the ideal shot. The EA method is then used to target the optimal shot location and shot size, which is done by using a fitness function based on a method designed by Ferris et al. [6]. In this approach a set of objective functions formulated in equations 1-3 were developed:

$$\oint_{sh} (x, y, z) := (\text{spread}\,(x, y, z) - \text{height}\,(x, y, z))^2 \tag{1}$$

$$\oint_{sw}(x, y, z, w) := (\text{spreads}\,(x, y, z) - w)^2 \tag{2}$$

$$\oint_{hw}(x, y, z, w) := (\text{height}\,(x, y, z) - w)^2 \tag{3}$$

Where spread is represented by the approximate Euclidean distance between the current skeleton location and the end- point at which we started. Height is the approximate Euclidean distance to the nearest target boundary. W is to represent the size of the shot.

The first function, Eq. 1, ensures that the target volume is maximized as well as ensuring the current spread between shots has a minimized distance to the closet target boundary. . And then, the second function Eq. 2 is used to choose a helmet size that fits the skeleton best for the current location. At last, the third function Eq. 3 favors a location that is the optimal distance from the target boundary for the current shot size.

To guarantee that the height, the spread and the shot size *w* are as close as possible, the fitness function is represented as the sum of these three squared differences between three quantities. After every shot is placed on the target, the fitness function ensures that the target area will receive maximum coverage of the radiation and the surrounding normal tissues will receive minimum radiation to avoid harm. The fitness function is given as follows:

$$F = \oint_{sh} (x, y, z) + \oint_{sw}(x, y, z, w) + \oint_{hw}(x, y, z, w) \tag{4}$$

The key steps of EA-based shot location and size selection are described as follows:

1. First population initialization:
1.1 Detect all end points based on the skeleton of targets
1.2 Detect the boundary points of targets
1.3 Encode the first population: Permutation coding technique is used to initialize the population. All points on the skeleton are represented by a one- dimensional integer string. One integer denotes one point. For instance, there are five points on the skeleton in total. The first population in this case can be decoded into a five integers string, which looks like (1 2 3 4 5).
1.4 *Set EA operator parameters:* The crossover rate (*Pc*), the mutation rate (*Pm*), the desired fitness value, and the number of generations (*Ng*) are all defined at this step.

2. First generation initialization: The first generation is *m* points, which are selected randomly from all the point in the skeleton. They are treated as chromosome. Normally, the number of the first generation is set as 10 percent of whole population. For example, if the skeleton of a target has 1000 points (voxels). The first generation may contain 100 points.

3. The new generation reproduction: EA operators, mutation and crossover, are run in this step to generate the new generations. As mentioned above, single point crossover and order changing mutation are applied.

4. Evaluate the fitness of the points in both generations: The quality of each chromosome (point) is evaluated by a fitness value, and the purpose of optimization is to find the individual with minimum fitness. The fitness value of each chromosome is calculated by fitness function F (1), which is explained above. The distance between each chromosome to the boundary, the distance between each point to the end points and the shot size will be compared to each other in this step. The fitness values of all the points are stored in a one-dimensional sequence, which is prepared for the following steps [13], [14], [15].

5. Sort all the points according their fitness value: After this operation, the chromosome in the both generations is sorted in ascending order.

6. *Approach the current best chromosome, and update generation:* According to the previous steps, if one of the points satisfies the desired fitness value, the EA stops. At this time, the best shot is chosen. Otherwise, the points that corresponding to the first m fitness value based on step 5 are selected to run in new loop. The rest of the points are removed both from sequences and the population.

7. *Terminated EA:* The optimization process will be terminated if the predefined desired fitness value is satisfied, or the algorithm has run *Ng* generations. The point, which has the smallest fitness value, is the best shot. The rest of the target is considered in whole as a new target. Steps 1 to 6 are repeated until the smallest shot size cannot be inserted into the rest of the target.

3. RESULTS OF COMPUTATION

EA-based shot placement model was tested in several simulated targets with different shapes and sizes. The simulated targets are both in two-dimensional and three- dimensional.

Table 1 Execution Time of Five Targets

Target	Target Size	Shot Sizes	Number of shots
1	35mm by 35mm	4mm 8mm 14mm 18mm	2 3 4 1
2	15mm by 35mm	8mm 14mm	2 1
3	20mm by 15mm	8mm 14mm	2 1
4	25mm by 25mm by 10mm	14mm	4
5	35mm by 35mm by 35mm	4mm 8mm 14mm 18mm	2 3 4 1

Initially two dimensional targets were tested and then, the tests were expanded on to three dimensional targets. The algorithms in this model are coded in Matlab, and run by using Matlab R2015b in an Dell laptop with 3.1 GHz Intel Core 2 Duo processor and 4.0 GB DDR2 667 RAM. To test its robustness, the proposed model independently runs 5 times for each of the cases. The following are several two-dimensional and three- dimensional examples that show the resulting of EA based shot location and size determination solution. Neurosurgeons commonly use isodose curves as means of judging the quality of a treatment plan. They wish to impose a requirement that the entire target is surrounded by an isodose line of x%.

In this section, results generated by EA-based shot placement model are compared based on three different attributes: 1. Execution time before the optimum solution is found, 2. How many shots to be chosen, and 3. Coverage on targets.

The lines depict each specific fraction of the target that is covered by shots, which receives a particular dosage. The blue line representing the 4mm shot declines faster than the lines representing the bigger size shots. While the line representing the 18mm shot decreases slightly.

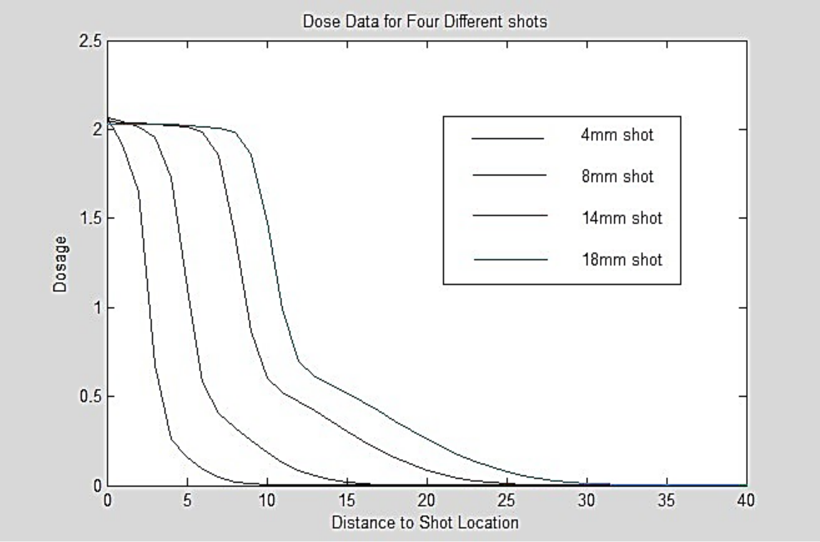

Figure 1: Dose Data for Four Different Shots

The isodose curves higher than 50% are generally considered having effective execution. For case of does variation from 0 to 2, different shots has different radius of effective execution. Only those voxel that embraced by that radius can receive adequate dosage and be cued efficiently. The following table lists the radius of effective execution for different shots in this approach.

Table 2 Radius of Effective Execution

Radius of Effective Execution	Shot
2.67mm	4mm
5.21mm	8mm
8.75mm	14mm
10.97mm	18mm

The optimized solutions for all of the five targets are shown in Table 3, together with execution time for all of targets. Ordinal shot location and size determination technique is compare with EA-based model. Ordinal SLSD is similar to EA-based shot placement, but it evaluates skeleton points one- by-one in a sequence rather than select points randomly. EA- based model takes less time to execute Target 1, 4 and 5 than ordinal SLSD does. There three targets are more irregular and larger (three-dimensional) than the other two. However, for simple and small two-dimensional examples, like Target 2 and 3, execution time generated by EA-based model are not less than that of ordinal ones. It can be concluded that, EA-based model has faster performance on irregular or three-dimensional cases. It can speed up the shot location and size determination procedures. On the other hand, all optimized solutions cover above 90% of the targets with number of shots less than 15. EA-based shot placement model is a useful tool for assisting in the selection of the appropriate number of shots and shot sizes. Also they demonstrated that this model satisfies the requirements of optimal treatment planning [14], [15].

Table 3 Radius of Effective Execution

Target	**Execution time**		**Coverage by 50% Isodose**
	EA-based	**Ordinal**	
1	39 seconds	63 seconds	92%
2	23 seconds	23 seconds	90%
3	29 seconds	27 seconds	96%
4	109 seconds	243 seconds	95%
5	135 seconds	N/A	94%

CONCLUSION

In this paper, a variety of modeling and techniques are used to develop a model for solving the shot location and size determination problem in Gamma knife treatment planning. The skeleton generation methods can speed the process of shot placement, and improve the effectiveness of optimization- based model. The EA-based shot placement model can help treatment team to place an optimum shot quickly and precisely. The methods and approaches applied here can generate more effective and better treatment plans in shorter time. The EA- based shot location and size determination model is a useful tool in the selection of the appropriate number of radioactive shots and shot sizes. There are limitations on the model, and more work needs to be done for improving the model used in this thesis. At first, the actual shape of shots is not perfectly spherical, but slightly distorted. In future works, ellipsoids may instead of spheres to fit shots in the target. Additionally, the model has not been tested on actual patient data. Whether the model can handle the real medical cases with very irregular shapes needs to be examined in future. Finally, there is no guarantee that there is not a better solution. It is best if Pareto analysis is used to rank and identify promising solutions and other bio-inspired optimization techniques such as Bess algorithm and Ants Colony be considered for solution.

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