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An open-source genetic algorithm for determining optimal seed distributions for low-dose-rate prostate brachytherapy

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ABSTRACT

PURPOSE: An open source optimizer that generates seed distributions for low-dose-rate prostate brachytherapy was designed, tested, and validated.

METHODS: The optimizer was a simple genetic algorithm (SGA) that, given a set of prostate and urethra contours, determines the optimal seed distribution in terms of coverage of the prostate with the prescribed dose while avoiding hotspots within the urethra. The algorithm was validated in a retrospective study on 45 previously contoured low-dose-rate prostate brachytherapy patients. Dosimetric indices were evaluated to ensure solutions adhered to clinical standards. The SGA performance was further benchmarked by comparing solutions obtained from a commercial optimizer (inverse planning simulated annealing [IPSA]) with the same cohort of 45 patients.

RESULTS: Clinically acceptable target coverage by the prescribed dose (V_{100}) was obtained for both SGA and IPSA, with a mean ± standard deviation of 98 ± 2% and 99.5 ± 0.5%, respectively. For the prostate D_{90}, SGA and IPSA yielded 177 ± 8 Gy and 186 ± 7 Gy, respectively, which were both clinically acceptable. Both algorithms yielded reasonable dose to the rectum, with $V_{100} < 0.3$ cc. A reduction in dose to the urethra was seen using SGA. SGA solutions showed a slight prostate volume dependence, with smaller prostates (<25 cc) yielding less desirable, although still clinically viable, dosimetric outcomes. SGA plans used, on average, fewer needles than IPSA (21 vs. 24, respectively), which may lead to a reduction in urinary toxicity and edema that alters post-implant dosimetry.

CONCLUSIONS: An open source SGA was validated that provides a research tool for the brachytherapy community.

Keywords: Prostate brachytherapy; Low dose rate; Optimization; Seed distribution; Open source; Genetic algorithm

Introduction

Low-dose-rate prostate brachytherapy (LDRPB) is a method of treating prostate cancer through interstitial implantation of small, radioactive seeds throughout the prostate. Numerous regimens have been carried out where LDRPB has been used as either a monotherapy or in conjunction with external beam radiotherapy (EBRT) or hormonal therapy for the treatment of various stages of prostate cancer (1–9). The American Brachytherapy Society has provided an extensive overview and consensus on the prescriptive recommendations for LDRPB, from patient selection, workup, prescription dose, treatment, post-implant dosimetry, and followup (10, 11). LDRPB has shown its greatest treatment efficacy as a monotherapy for early stage, localized prostate cancer. The desired outcome for any radiation therapy treatment is achieving a conformal distribution of the prescribed dose to the target structure while minimizing the damage done to surrounding healthy structures. While LDRPB is able to provide comparable target coverage to EBRT, it has the added benefit that radiation does not traverse healthy tissue to reach the target structure, resulting in reduced dose to healthy normal tissue. This reduced damage to healthy structures facilitates the ability of LDRPB to escalate the dose to the target when compared with EBRT.

However, for LDRPB, the resulting dose distribution is highly dependent on the placement of the seeds within

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the prostate. A poor seed distribution can lead to underdosage of the target structure, as well as overdosage of the surrounding healthy structures. Over the past 3 decades, an extensive amount of research has been taken up with regard to optimizing the seed arrangement that will, in turn, result in a desirable dose distribution for a given prostate patient (12–23).

This breadth of research on seed placement optimization led to the commercialization of optimization algorithms that can rapidly and efficiently generate a seed distribution that provides adequate dose coverage to the target while minimizing dose to healthy structures for most organ geometries. However, there have been some limitations to its success in the clinics where the clinically implemented seed distributions are usually a combination of computer-generated seed distributions and the operator's manual intervention. Although this commercialization has been beneficial for current clinical practice, it does not provide a sufficiently broad platform for further research and investigation that could lead to a more dosimetrically desirable outcome or reduced need for manual intervention and standardization of the procedure for generating reasonable seed distributions. Modern computer algorithms are complex and can interact in a variety of non-intuitive ways, no longer based on a set of simple instructions. Commercial clinical software is also based on copyrights, patents, and legal liability. This restricts the ability to perform quality control of software under various clinical scenarios. In certain cases, the software may not perform as intended by the designer. Recently, there has been a drive to ensure accountability and independent auditing of computer algorithms while staying within the legal jurisdictions. A real open source algorithm can open doors to scrutinize the software but also provides independent quality assurance of clinically used software. An example of the demand and need for open-source software and platforms is evident by the amount of publications that have come out due to the availability of relatively recent radiotherapy treatment planning platforms, such as Computational Environment for Radiotherapy Research (CERR) (24), 3D Slicer (25), and slicerRT (26). Therefore, to further advance optimization of radioactive seed distributions for brachytherapy, the purpose of this study was twofold: (*1*) To create an open source optimization algorithm that can generate a clinically acceptable seed distribution for a given set of patient contours using commonly available software tools. (*2*) To validate and benchmark the open-source optimization with a commercial optimizer. Both tasks were realized by performing a retrospective study on a data set of 45 previously contoured prostate patients, where solutions were generated and compared with ones obtained by a commercial optimizer.

The open-source optimizer in this study was built around the genetic algorithm (27). There have been some investigations regarding permanent prostate implant optimization using a genetic algorithm as the solver (13, 15). These studies have focused on implementing the genetic algorithm on a simplified, ellipsoidal prostate model. Therefore, in addition to providing an open-source, research-ready optimizer, this study differs from the previous in that a relatively large set of real prostate patient files, varying in urethral complexity and prostate volume, was used to test and validate the optimizer.

Methods

Simple genetic algorithm

This is a stochastic algorithm that uses concepts based on principles of Darwinian Natural Selection (27). Initially, a population of 41 random seed distributions is generated. Four operators: elitism, roulette wheel selection, single-point crossover, and single-point mutation operators (Fig. 1) have a user-assigned probability of acting on each seed distribution to generate a new population for the next iteration. The theory suggests that the action of these operators leads to fitter individuals, which in this application are represented by radioactive seed distributions. The elitism operator ensures the optimal solution of the current iteration is not lost by allowing it to pass unaltered to the next iteration of the algorithm. Roulette wheel selection is used to determine which parent seed distributions will be used to create the new distributions for the next iteration. The probability of being selected as a parent is proportional to the individual seed distribution's fitness score; therefore, fitter seed distributions will have a higher probability of being selected. Once the parents have been selected, the new seed distributions are generated through the action of the single-point crossover and mutation operators. The single-point crossover picks a crossover point between a pair of parent distributions and exchanges the portion of the distributions after this crossover point. The single-point mutation operator works by randomly selecting a point where the distribution is mutated by adding or subtracting a seed, based on the current configuration of the seeds. The user-defined objective function then calculates a fitness score for each distribution. The fitness score is a reflection of the distribution's ability to meet the predetermined optimization criteria. For LDRPB, the desired optimization criteria are to minimize the number of needles and seeds used while covering the entire planning target volume (PTV) with a uniform prescribed dose (144 Gy) while reducing the damage to the surrounding healthy structures, such as the urethra, rectum, and bladder. For simplicity, the urethra was the only critical structure considered in the objective function when determining the optimal seed distribution. The maximum number of iterations assigned to the simple genetic algorithm (SGA) was 25,000, which was determined through trial and error. Once the algorithm reached this iteration threshold, the seed distribution with the highest fitness score was taken to be the optimal solution. The SGA algorithm was encoded and implemented in MATLAB