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Demonstration of simulated annealing optimization for permanent breast seed implant treatment planning

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ABSTRACT

PURPOSE: Permanent breast seed implant (PBSI) is a developing brachytherapy technique for the treatment of early-stage breast cancer. In current practice, PBSI uses manual planning strategies to generate clinical treatment plans. In this work, a simulated annealing-based algorithm is developed to demonstrate the first application of inverse optimization for PBSI.

METHODS AND MATERIALS: Target, skin, and chest wall muscle contours, exported from a treatment planning system in digital imaging and communications in medicine format, are used as inputs. To optimize, the user defines the dose−volume histogram objectives for the target and specifies a relative weighting for target and skin constraints. A 10-patient cohort of previously treated patients was planned by using the inverse optimization algorithm. Plan quality was compared to the clinically treated manually generated plans using the $V_{90\%}$, $V_{100\%}$, $V_{150\%}$, and $V_{200\%}$ for the planning target volume (PTV), $V_{90\%}$ and $D_{0.2\text{ cc}}$ for skin dose, and PTV conformity indices.

RESULTS: For each of the 10 patients, patient-wise paired differences between inverse and manual plans were analyzed and presented in box plots. Comparing inverse and manual planning techniques, a statistical difference was not observed ($p > 0.05$) in PTV coverage criteria ($V_{90\%}$, $V_{100\%}$) and dose to $\text{skin}_{2\text{mm}}$. A statistical difference was observed in the inverse plans as a reduction of the $V_{150\%}$ (mean of 6.2%) and increase in conformity index of the 20%, 50%, 90%, and 100% isodose lines.

CONCLUSIONS: This work presents the first application of inverse optimization used to generate PBSI treatment plans. A 10-patient cohort previously treated with PBSI was retrospectively planned for comparison with the clinically treated manually generated plans. © 2018 American Brachytherapy Society. Published by Elsevier Inc. All rights reserved.

Keywords: Permanent breast seed implant; Brachytherapy; Inverse planning; Simulated annealing; Optimization

Introduction

The standard of care for early-stage breast cancer has been established as lumpectomy followed by whole-breast irradiation (WBI), a treatment regimen that has been shown to have equivalent long-term survival to mastectomy (1, 2). In recent years, interest in the radiotherapy community has mounted in reducing the treatment time for early-stage breast cancer patients, which is made possible by only irradiating the original tumor site plus a margin; a treatment strategy termed accelerated partial breast irradiation (3). Treatment of a limited breast volume has been explored in a variety of high-dose-rate (HDR) multicatheter interstitial brachytherapy techniques, which have led to American Brachytherapy Society consensus guidelines on its utilization (4). PBSI (5) is another breast brachytherapy technique that was pioneered at the Odette Cancer Centre (Toronto, Ontario, Canada) in 2004 and uses low-dose-rate brachytherapy seeds. PBSI offers patients a condensed alternative to standard fractionated WBI and HDR breast brachytherapy. Inspired by permanent low-dose-rate prostate

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Conflict of interest: Michael Roumeliotis, Brock Yates, and Tyler Meyer are shareholders and Directors of Okolo Health Inc. which is involved in the manufacture and sale of equipment and software used in the permanent breast seed implant (PBSI) procedure.

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brachytherapy, PBSI is a 1-day procedure involving the surgical insertion of palladium-103 seeds in and around the postlumpectomy seroma. In 2015, Pignol et al. reported clinical outcomes for 134 patients with a median followup of 63 months and showed local recurrence rates comparable to nomogram-based estimates for WBI (6). In clinical practice, PBSI is manually planned. Although planning times have not been reported, our institutional practice requires hours of time commitment to generate a manual plan.

In 1996, Pouliot et al. (7) developed an inverse planning technique for use in permanent prostate brachytherapy using a simulated annealing algorithm. Incorporating both target coverage and dose uniformity in the optimization, the algorithm efficiently generated clinically acceptable plans. Updated versions of inverse planning simulated annealing have now been in successful clinical use for more than 2 decades for permanent prostate brachytherapy (8, 9), while the application of similar inverse optimization algorithms to other brachytherapy treatment sites have since been reported (10). In applying inverse optimization to PBSI, similar gains in the time required to generate plans as well as plan quality and consistency may be achieved.

In comparison to permanent prostate implants, PBSI planning and delivery presents a unique challenge for the inverse optimization problem. The use of a patient-specific implant angle as well as the presence of anatomical barriers (i.e., chest wall and skin) renders the PBSI implant process a different problem both clinically and computationally. With over 10 years of clinical treatments now ongoing, current commercial software packages for PBSI planning do not yet offer an inverse optimization solution. In addition, modification of existing optimization software to the PBSI planning aims is nontrivial. Consequently, all PBSI patients treated to this point have been planned using manual optimization techniques.

An inverse optimization algorithm was developed specifically for the PBSI problem and its functionality was tested by retrospectively applying the software to 10 previously treated patients. A comparison between the manually optimized clinical plans and the inversely optimized plans is reported. The purpose of this study is to demonstrate the application of inverse optimization for PBSI by developing an algorithm that not only allows for the rotation of the seed coordinate system to the patient-specific implant angle but also addresses the unique delivery considerations of PBSI by creating an optimization workflow tailored to the PBSI geometry.

Methods

Description of algorithm

Preprocessing

In PBSI, the seroma, chest wall, and skin are the anatomy-based volumes required to define both the implant geometry as well as the relevant plan dose metrics. The optimization algorithm requires planning target volume (PTV), chest wall, and skin contours. PTV and skin contours are required to guide dosimetric constraints during optimization. Knowledge of the chest wall contour is also required because the chest wall provides an anatomical barrier through which needles are not permitted to traverse during the seed delivery. Contours can be produced in any software that will save and export contour points in digital imaging and communications in medicine (DICOM) format.

A preprocessing step, referred to as the parsing phase, is used to define all potential seed locations. The implant angle is user specified, typically selected to be tangential to the chest wall near the seroma. To allow possible seed locations outside the PTV, the points on the PTV contour are expanded by a user-defined margin to create an expanded PTV that defines the possible seed locations. A three-dimensional grid is generated from the center of the expanded PTV, corresponding to the 5×5 mm^2 grid block of the delivery template and a 5-mm distance between successive seeds within a needle track (i.e., seeds can be placed end to end without a spacer automatically inserted between them). Any possible seed locations available within the skin or chest wall are cropped. An example of the possible seed locations, showing conventional peripheral loading, is shown in Fig. 1 to illustrate the results of the parsing phase.

General description of simulated annealing

An overview of the simulated annealing optimization algorithm is provided, with greater detail available in original references (7). A simulated annealing algorithm describes the optimization problem in terms of a state with an "energy" and "temperature" in analogy with the "cooling" of a material into a microstate where the molecules have minimum energy. Simulated annealing algorithms are characterized by expressions of the form

$$P(i) = e^{\frac{-[f(i)-f(i-1)]}{T(i)}}, \tag{1}$$

where $P(i)$ defines the probability of accepting the test state at iteration i. The objective function, f, is used to provide an objective metric of the quality of the solution and is the quantity that is minimized in analogy with the energy of cooling molecules during annealing. A temperature parameter, $T(i)$, is a function that decreases with successive iterations. Equation (1) demonstrates that simulated annealing is a stochastic algorithm that may accept solutions at iteration, i, with a higher objective function value, $f(i)$, than the current solution, $f(i-1)$. This allows the optimization process to escape local minima, where the iteratively decreasing temperature term serves to reduce the probability of escape as the system cools through iterations. Simulated annealing implementations coordinate this decreasing probability of accepting a worse solution with an efficient