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Examining the relationship between pre- and postimplant geometry in prostate low-dose-rate brachytherapy and its correlation with dosimetric quality using the similarity concept

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ABSTRACT

PURPOSE: This is a retrospective study in which we define multiple metrics for similarity and then inquire on the relationship between similarity and currently used dosimetric quantities describing preimplant and postimplant plans.

METHODS AND MATERIALS: We analyzed a unique cohort of 94 consecutively performed prostate seed implant patients, associated with excellent dosimetric and clinical outcomes. For each patient, an ultrasound (US) preimplant and two CT postimplant (Day 0 and Day 30) studies were available. Measures for similarity were created and computed using feature vectors based on two classes of moments: first, invariant to rotation and translation, and the second polar–radius moments invariant to rotation, translation, and scaling. Both similarity measures were calibrated using controlled perturbations (random and systematic) of seed positions and contours in different size implants, thus producing meaningful numerical threshold values used in the clinical analysis.

RESULTS: An important finding is that similarity, for both seed distributions and contours, improves significantly when scaling invariance is added to translation and rotation. No correlation between seed and contours similarity was found. In the setting of preplanned prostate seed implants using preloaded needles, based on our data, similarity between preimplant and postimplant plans does not correlate with either minimum dose to 90% of the volume of the prostate or analogous similarity metrics for prostate contours.

CONCLUSIONS: We have developed novel tools and metrics, which will allow practitioners to better understand the relationship between preimplant and postimplant plans. Geometrical similarity between a preplan and an actual implant, although useful, does not seem to be necessary to achieve minimum dose to 90% of the volume of the prostate-good dosimetric implants.

Keywords: Prostate cancer; Permanent seed implant; Implant quality; Similarity

Introduction

Transrectal ultrasound—based prostate brachytherapy

Over the past few decades, transperineal ultrasound (US)—guided prostate brachytherapy has been increasingly used as a definitive treatment for early stage carcinoma of the prostate. Real-time guidance using transrectal US imaging allows the radioactive seeds to be inserted into the prostate in a precise and predictable fashion. The actual insertion is carried out mostly using either a Mick applicator (Mick Radio-Nuclear Instruments Inc.) or preloaded needles. The seeds and spacers can be loose or linked.

After Holm (1) described the first method of transrectal US—guided perineal brachytherapy (2), several techniques have been developed and are in current practice for permanent prostate brachytherapy. Although not completely distinct in practice nor the only ones, the two main approaches in planning are the preplanning, where a plan is produced well ahead of the implant date, and the intraoperative planning, where a plan is produced at the time of the actual procedure. A certain degree of interactivity and feedback can be present in the delivery phase irrespective of the planning method. Using either approach, the goal of

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the procedure is to ensure an accurate seed placement within the target volume. Regardless of planning and implant techniques, there are significant limitations in accurate seed positioning, leading to significant deviations from plan, because of a number of factors, including needle deviations, gland movement, interseed geometry changes as a result of tissue compression, retraction, edema, and so on. Although the most important metric in implant quality is clinical outcome, dosimetric parameters are routinely used as surrogates. The current recommendations on dose reporting for permanent seed implants for prostate cancer include dosimetric quantities, among which minimum dose to 90% of the volume of the prostate (D_{90}) occupies an important place. Some authors, however, report good correlation between clinical outcome and D_{90} (3), whereas others find the two to be poorly correlated (4). Spatial and temporal dose rate variations within an implant are likely to confound the utility of parameters like D_{90}, volume (of prostate) receiving 100% of the prescription dose (PD), and others making them insufficient as surrogates of the biological response of prostate cancer to radiation, which involves the complex relationship between spatial−temporal patterns of dose delivery and the underlying cell kinetics of various cell populations. In this study, we will only focus on examining the significance of spatial similarity of seed arrangements for the D_{90} as a quality indicator.

The very idea of planning implies that the actual implant is expected to have some resemblance with the plan. We believe that the current practice of creating a preimplant plan, whether days or minutes before the actual implant, begs the question of similarity: Are in fact the real implants similar with their plans and is this similarity (or lack thereof) affecting currently used dosimetric parameters? The similarity between a plan and its implementation is never questioned in external beam radiation therapy, where we strive to deliver plans at the limit of error and uncertainty allowed by technology; these errors and uncertainties are, as it is well known, much larger in prostate brachytherapy, so we felt this is an important question to ask.

Recently, the Nuclear Regulatory Commission (NRC) and some professional societies have aimed to change the definition of medical event from a dosimetric-based one to strength based, in which a certain percentage of seeds are required to be deposited within the treatment site. Thus, a formal inquiry on geometrical similarity, based on a large clinical data set, seems timely and would likely shine some light on the relationship between geometrical properties of prostate implants at various time points.

Our contributions

The article has three goals: first, to describe a formalism that can be used to quantify similarity between three-dimensional (3D) data sets; second, through this formalism, to quantify similarity of seed distributions and contours in preplans vs. postimplant plans in prostate brachytherapy; and third, to examine the relationship between similarity and dosimetric parameters. To the authors' knowledge, this is the first exploration on the idea of geometrical similarity in the context of prostate seed implants.

First, we examine what type of similarity formalism is most suitable to describe prostate implants.

Intro on the similarity issue. What is the best way to compute it?

Given two sequences of points in 3D space, $P = [p_1, p_2, \ldots, p_n]$ and $Q = [q_1, q_2, \ldots, q_n]$, their coordinate root mean square deviation (cRMSD) can be used as a measure of similarity:

$$\mathrm{cRMSD}(P,Q) = \min_T \sqrt{\frac{1}{n}\sum_{i=1}^{n} \|p_i - Tq_i\|^2},$$

where $\| \cdot \|$ is the Euclidean L_2-norm and T is a rigid transformation (translation and rotation).

This way of defining similarity implicitly assumes the existence of two elements:

1. Matching—that is a one to one "map" between the elements of the two distributions (for each p_i, one can identify the *corresponding* q_i) and
2. registration—there is a rigid transformation T such that the root mean square distance between elements in A and those in T(B) is less than some threshold ε.

In practice, for complex volumes, a complete match of this sort is rarely possible and the computation of cRMSD is typically ill conditioned. For example, preplans and postimplant plans seldom have the same number of seeds, and for all practical purposes, seeds, which are indistinguishable, cannot be completely matched (in the sense of matching seed p_i from a preplan with its correspondent q_i from a postimplant plan). Likewise, contours cannot be digitized or created (at least not easily) with the same number of points located in identical places on separate renderings of a structure, particularly if the images depicting contoured structures are acquired in different imaging spaces (e.g., US and CT).

An alternative to the matching and registration technique described previously, the use of moments and moment invariants is less confounded. These were introduced by Hu (5) who derived his seven well-known invariants to rotations in two dimensional. Although their most frequent use is as shape descriptors, invariant moments suffer from globalness as an intrinsic limitation; for our purpose, this becomes a strength as moments are not too sensitive to individual displacements but rather to the general spatial pattern.