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Needle and seed segmentation in intra-operative 3D ultrasound-guided prostate brachytherapy

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Abstract

In order to guide the needle to the correct location in 3D US-guided brachytherapy, the needle is continuously tracked as it is being inserted. A pre-scan before the needle insertion and a post-scan after the needle insertion are subtracted to obtain a difference image containing the needle. The image is projected along two orthogonal directions approximately perpendicular to the needle, and the 3D needle is reconstructed from the segmented needles in the two projected images. The seeds implanted with the needle are located in the cropped volume along the needle. Thus, the seeds are segmented using a tri-bar model and 3D line segment patterns. Finally, the positions of the seeds are determined using a peak detection technique. Experiments with agar and turkey/chicken phantoms as well as patient data demonstrated that our needle segmentation technique could segment the needle in near real-time with an accuracy of 0.6 mm in position and 1.0° in orientation. The true-positive rate for seed segmentation is 100% for the agar phantom and 93% for the chicken phantom. The average distance to manual seed segmentation was 1.0 mm for the agar phantom and 1.7 mm for the chicken phantom.

Keywords: Needle segmentation; Seed segmentation; Prostate brachytherapy; 3D ultrasound imaging; 3D US guidance

1. Introduction

Prostate cancer is the second leading cause of cancer death in Northern American men, especially for individuals over 50. In 2004, there were 230 110 new prostate cancer cases in USA, and 29 900 American men died from prostate cancer [1]. In Canada, according to Canadian Cancer Statistics in 2004, there were 20 100 new prostate cancer cases, and 4 200 Canadian men died of prostate cancer [2]. Fortunately, prostate cancer is curable if it is diagnosed correctly in its early stages and treated properly by surgery or a therapy, such as radical radiotherapy/HIFU, brachytherapy/cryosurgery, or high dose radiation.

Prostate brachytherapy is a minimally invasive therapeutic technique for prostate cancer. It utilizes radiation from implanted seeds in the patient's prostate to destroy the cancer cells. Unlike radical radiation, it is associated with fewer complications and fewer hospital visits. The prostate brachytherapy procedure is composed of the following steps:

Step 1: *Dose pre-planning*. An optimized dose distribution is calculated based on the volume of the prostate, locations of other structures (e.g., rectal wall, urethra), and a radiation model of the seed (either I-125 or Pd-103). To produce such a distribution, the number of the seeds and their locations are planned using dose pre-planning software.

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Step 2: *Seed implantation*. Based on the pre-plan made in Step 1, the physician uses brachytherapy needles to implant the seeds into the patient. Usually, 3–5 seeds are dropped in the same needle insertion, with a total of 80–100 after about 20 needle insertions. In order to implant the seeds in their pre-planned positions, the physician determines the locations of the needle tip using a needle insertion template and observing the inserted needle depth under 2D ultrasound (2D US) guidance. This approach is tedious, slow and subject to errors. In order to solve these problems, a 3D US image-guided system has been developed in our laboratory [3]. Thus, a fast and accurate needle segmentation method using the 3D US image is critical.

Step 3: *Dose post-planning*. Due to the migration of the seeds, as well as deformation of the soft tissues during the needle insertion and withdrawal, the actual positions of the seeds may not coincide with the pre-planned positions. Thus, recalculation of the actual dose distribution is necessary. In order to calculate the actual dose distribution during the implantation phase of the procedure, when implantation errors can be corrected, the position of each seed must be accurately determined. To perform this task, we must develop an efficient seed segmentation method using 3D trans-rectal (3D TRUS) images.

In this paper, we discuss our developments of brachytherapy needle and seed segmentation from 3D TRUS images. The paper is organized as follows: Section 2 introduces the needle and seed segmentation methods, in which the seed segmentation is based on the needle segmentation. In Section 3, experimental demonstrations are described including different phantoms and patient data used in our experiments, the experimental setup and the 3D US imaging system. The discussion and conclusion is presented in Section 4.

2. Needle and seed segmentation

Needles are frequently used in interventional procedures such as brachytherapy and biopsy. The depth of needle insertion varies from a few millimeters to a few of centimeters. Our needle segmentation method is based on the following assumptions:

1) The needle is straight and its deflection is negligible.
2) The approximate needle position and orientation are known either from manual insertion or the 3D imaging system and
3) One needle is required to be segmented at a time.

Our method is based on reconstruction of the needle in 3D from detection of the needle from its two orthogonal 2D projections [4]. This procedure is composed of the following steps:

Step 1: *Difference image acquisition*. In order to simplify the background, a change detection technique is used first. The 3D US image containing a needle is subtracted from the 3D US image prior to the insertion of the needle in order to obtain a difference image containing the inserted needle. In this image, any background including tissues, bones, and calcification will disappear, greatly simplifying needle segmentation and tracking tasks in the 3D US images.

Step 2: *Volume cropping*. Using the approximate information about the needle trajectory from either the manual insertion or the 3D US imaging system, the volume in the difference image is cropped to a rectangular region containing the needle. This procedure decreases the amount of data to be processed and further simplifies the background used for segmentation.

Step 3: *Projection using a volume rendering technique*. The purpose of this step is to obtain the projected 2D images and increase the contrast of the needle. A Gaussian function representing the gray level distribution of the needle voxels is used as the opacity and luminance transfer functions in volume rendering. The two parameters of the Gaussian function, mean $\bar{I}$ and variance σ^2, are estimated from manually segmented sample images. The cropped volume is projected along two orthogonal directions perpendicular to the approximate needle direction to obtain two orthogonal views containing the needle.

Step 4: *Needle detection in 2D images*. Two techniques have been used for needle detection in the 2D images. In the case of a simple background, it is assumed that the largest object in the cropped volume is the needle. Thus, needle detection is performed by simple thresholding followed by a flood-fitting algorithm [4]. For a more complicated background, a real-time Hough transform technique as described in Ref. [5] is used.

Step 5: *3D needle segmentation*. After Step 4, the needle projections in the two orthogonal views are known. With the detected needle directions and the projection directions, the 3D needle direction can be calculated [4]. Furthermore, the endpoints of the needle are estimated.

Seed segmentation is challenging for three reasons. Firstly, the seed dimensions are small, typically a cylinder 4.5 mm long cylinder and with a diameter of 0.8 mm. Secondly, a large number of seeds are implanted, (from 80 to 100). Third, there are other bright points in the 3D US image with similar gray levels to the seeds. These points arise primarily from calcifications in the prostate. In order to solve these problems, we developed a seed segmentation method based on the needle segmentation approach, composed of the following five steps [6]: