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Needle Identification in High-Dose-Rate Prostate Brachytherapy using Ultrasound Imaging Modality

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***Abstract*— It was observed that the needle tip identification in high-dose-rate (HDR) prostate brachytherapy is challenging due to various uncertainties. The errors in identifying the correct needle position and angulations could compromise patient treatment outcomes. In this article, we propose a method for the needle identification using real-time ultrasound images obtained during the treatment procedure. The developed algorithm is capable to detect both the needle tip in a predefined coordinate system and the needle deflection angle for each frame of the incoming real-time ultrasound video streams.**

I. Introduction

Prostate cancer is a type of cancer that develops in the prostate gland. An estimated 241,740 new cases of prostate cancer are expected in 2012, accounting for about 15% of all cancer diagnoses (male and female) in the US population. It was found that many patients can be cured if their prostate cancer has not spread. An estimated 28,170 deaths, accounting for about 9% of all cancer deaths in male population, are expected to occur in 2012 (American Cancer Society Cancer Facts & Figures 2012), [1]. The treatment of such patients depends on various facts, including health conditions and the Gleason score. The treatment techniques include surgery, external beam radiation therapy (EBRT), hormonal therapy, and radioactive seed implants, called low-dose rate (LDR) brachytherapy. The use of LDR technique alone or with EBRT is increasing for patients, including about one third of US men who are diagnosed annually with prostate cancer.

Brachytherapy is a method of treatment in which sealed radioactive sources are used to deliver radiation at a short distance by interstitial, intracavitary, or surface application. With this mode of therapy, a high radiation dose can be delivered locally to the tumor with rapid dose falloff in the surrounding normal tissue, [2]. LDR prostate brachytherapy (typically <2 Gy/hr) is a method of delivering radiotherapy by implanting radioactive sources into and around the prostate gland, [3].

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However, with developments in computer controlled after-loader technology, Fig.1, the technically advanced type of brachytherapy called high dose rate (HDR) arises. Using this technique it is possible to increase the dose rate to more than 12 Gy/hr. Consequently, the course of treatment can decrease from weeks to minutes, comparing to other types of radiation treatment. The other advantages of HDR over LDR can be structured as patient, and target volume specific. HDR significantly improves the radiation dose distribution secondary to the ability to control the source position accurately and vary the source dwell time during treatment. There are also advantages in radiation safety and protection since the patient is not radioactive when he returns home [4]. After the treatment the radioactive source is retracted from the patient. The intraoperative optimization used with HDR allows better source position targeting with the potential for limiting treatment toxicity, [5-7]. In addition, radiobiological studies suggest that the hypofractionated treatment regimen delivered by HDR brachytherapy is thought to be advantageous for prostate cancer in particular, which is characterized by a low α/β ratio (1.5 – 3.7 Gy) [8-10], where α and β are parameters in cell survivals curve. The linear and quadratic contributions to cell killing are equal at a dose that is equal to the ration of these parameters.

In HDR brachytherapy, approximately 18 transperineal catheters with needles are used to deliver a heterogeneous distribution of dose, with large values of volume that received 125% of prescription dose (V125) and V150 in the

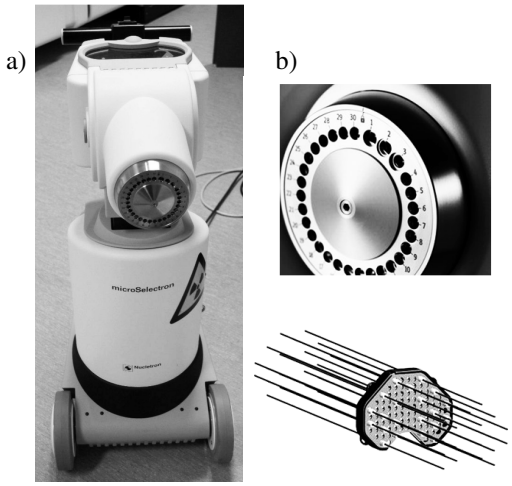

Fig. 1. a) Afterloader for the temporary insertion of Ir-192 source for the treatment of prostate cancer; b) Channels for connection of transfer tubes that guide the source through the hollow needles inserted into patient

peripheral zone of the prostate. This corresponds to the disproportionately greater number of cancer cells in the prostate periphery, as revealed on histologic examination, [11]. Since the prescription dose in single fraction for this type of treatment is 15 Gy, it is of great importance to identify the needles accurately on the images used for treatment planning. For example, at a point located 2 mm distally from the needle tip a needle deviation of ±1 mm leads to a dose variation between 274% and 58% for a 40.7 cGy cm^2 /h source of an HDR afterloader, [12]. The phantom study performed in ideal conditions reveals the errors between 0.8 and 3.1 mm for manual detection of the needle tip in ultrasound images by one observer in the transverse direction, and between 0.8 and 2.8 mm in the sagittal direction, [12]. To increase the treatment accuracy several methods were reported. A system for *in vivo* tracking of Ir-192 source during HDR brachytherapy treatments has been built using silicon pad detectors as image sensors and knifeedge lead pinholes as collimators, [13]. Another method using the miniature tissue-equivalent detectors with a high spatial resolution was suggested in [14]. The needle identification using different image modalities, such as fluoroscopy and combination of US and magnetic resonance imaging (MRI), was analyzed as well. A method of using the needle detection and tracking technique to compensate the breathing motion in 2D fluoroscopic videos was reported in [15]. Using the fusion of pre-operative MRI and real time intra-procedural transrectal ultrasound (TRUS) to guide prostate biopsy has been shown as a very promising approach to yield better clinical outcome than the routinely performed TRUS only guided biopsy, [16]. A novel method, [17] uses measurements of the residual needle length and an offline pre-established coordinate transformation factor, to calculate the needle-tip position on the TRUS images for HDR procedures.

In this article, we present the needle identification method capable of detecting both the needle tip and needle deflection. The method is suitable for clinical implementation since no additional measurements or detectors need to be used. Moreover, this approach can automatically perform needle segmentation and potentially send the DICOM-RT images to the treatment planning software for improved real-time dosimetry.

II. Needle Identification

To extract the information about needle position from US images it is necessary to solve image segmentation problem where the segmentation process subdivides image plane into its constituents regions: needle and the rest of the image. In the analyzed case, the detection algorithm restricts the search in the vicinity of the inserted needle, since the rough estimation can be made based on the expected needle position in the template that has to be used during the HDR. The segmentation should stop when the needle is isolated from background. Two basic properties of the images, discontinuity and similarity to the predefined US images of the needles, are taken into account in the proposed algorithm. The linear edge segments of the needles have been detected using the modified Hough transform, [18].

To search for discontinuity, we convolve a mask with the image to calculate sum of product of the coefficients with the intensity levels contained in the region encompassed by the mask. Consequently, response R of each point at the image was

$$R = \sum_{i=1}^{n} w_i z_i \ , \qquad (1)$$

where z_i is the gray-scale pixel intensity associated with mask coefficient w_i. The mask coefficients were used to reduce blurring giving the specific pixels more importance in calculation. In this case, the mask coefficients were discrete approximation of two dimensional Gaussian distribution function, [19]. To enhance the US images we used the appropriate masks for several possible needle orientations. We denoted R_i as a response equation (1) of the masks. If the proposed algorithm finds the point where $|R_i|>|R_j|$, for all $j\neq i$, than the point is more likely associated with the line i.e. needle in our case. However, the algorithm can detect some other isolated points that had strong response. These points will be removed if they do not belong to the expected region of the image. Since we know the expected direction of the needle, the masks determination can be simplified. Consequently, we used masks and thresholded the output in the range of ±5° of horizontal line. The points that have stronger responses correspond to the directions of the needles. Due to strong noise in US images, the detected pixels do not characterize line completely. Consequently, the intensity discontinuities can be often found in the processed images. To solve that problem a modified Hough transform was used to link and assemble edge pixels into the meaningful edges.

In the following part, both the needle identification (segmentation) algorithm and procedure for clinical use are presented in greater details.

A. Needle Identification Algorithm

The principal steps of the needle identification algorithm have been presented here. The live images were recorded to the computer using the FlashBus MV Lite (Integral Technologies®) frame grabber. The process of image acquisition runs in a software thread independently of the needle identification and monitoring. Thus, it does not affect the algorithm execution unless irregularity is detected.

The identification algorithm should be robust enough to enable the precise detection of the signal (needle) in the presence of high noise typical for ultrasound images. At the same time, the algorithm should be 'light' enough to run in real-time without clogging the computing resources. For this purpose, we have designed a novel algorithm that is still undergoing rigorous testing. Due to the space limitation, we are discussing the top-level design of the algorithm and its results. The general steps of the needle detection algorithm are presented in the following part, as well as in Fig.2.

Step 1: The calculation of the vertical gradient to enhance horizontal edges in the image.

Step 2: Run a horizontal average filter to strengthen the long horizontal components in the image resulting from the previous step.

Step 3: The image is then thresholded to isolate the brightest pixels. Most of the pixels belonging to the needle were detected in this step. However, in most of the cases, the needle itself will not be fully detected after this part.

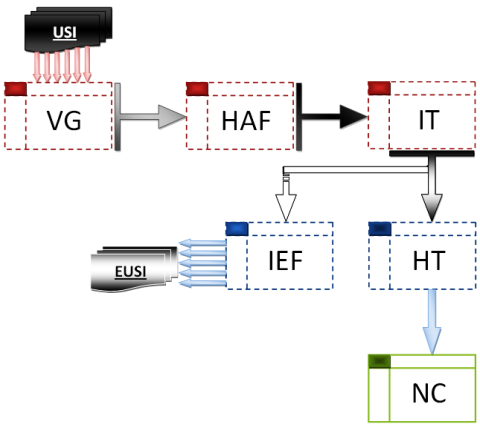

Fig. 2. The principal steps of needle detection algorithm; USI – ultrasound images from frame grabber, VG – vertical gradient calculation, HAF – horizontal average filter, IT – image threshold, IEF – image enhancer filter, HT – Hough transformation, EUSI – enhanced ultrasound images, NC – needle coordinate (position and orientation)

Step 4: For easier visualization, the original images were enhanced using the results from the previous step.

Step 5: Using the results from Step 3 the modified Hough transform (restricted to 0±5°) was calculated. As a result, a dominating line in normal form was formed with position r, and orientation θ. Based on the modified Hough transform [18], the algorithm is capable of providing information on the needle orientation (angulation, θ).

The desired insertion depth plays an important role in the identification. The estimation of the needle insertion depth is known from the HDR procedure itself and that information is used to restrict the search region where the needle tip can be found. As mentioned earlier, the process of the image acquisition runs in an independent software thread. If any irregularity in the expected needle position is found, the software can interrupt the main thread and/or modify the dose delivery as proposed below.

B. Proposed Clinical Procedure using Needle Identification

The workflow of the clinical implementation of the needle identification strategy can be divided into a few principal steps. The described procedure is only related to the implementation of the algorithm and it is not related to the overall clinical setup.

1) The uultrasound probe is rotated so the needle insertion can be continuously monitored in the sagittal mode.

2) The proposed algorithm for the new identification has been used to calculate the position of the needle tip as well as the current needle angulation. The algorithm has been described in the previous section.

3) The needle tip displacement from the predicted/desired position is evaluated and quantified in the treatment planning software.

4) If the displacement is within the preset limits the procedure can be repeated for the next needle. In that case, there is no need for correction in the treatment planning software.

5) If the displacement is above preset tolerance levels, i.e. if the detected needle position can compromise patient dosimetry and treatment, the following should be done:

- If it appears that the needle is not advanced to the predicted position, the probe should be rotated ±5° to find the correct imaging plane. After that, the needle tip position should be recalculated and the displacement has to be evaluated by physician. The proper correction should be entered into the treatment planning software which will recalculate the dosimetry parameters.

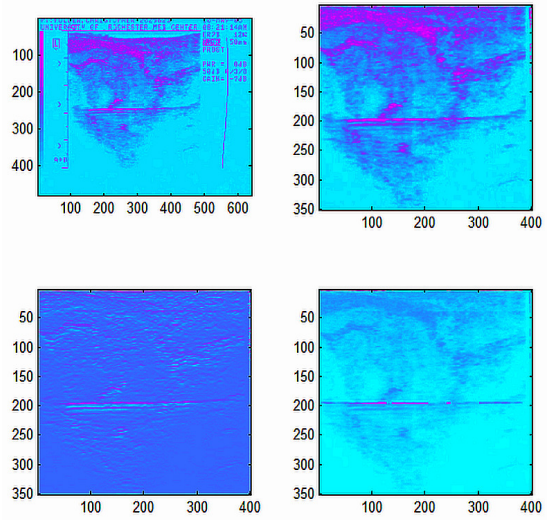

Fig. 3. The representative case and results for needle identification algorithm according in the general steps descriptions. The presented images are related to steps 1, 2, 3 and 5, respectively.

- The needle tip was detected in the vicinity of the expected position. However, the probe position and angular deflection tells about high needle deflection, the needle should be retracted, and the needle should be inserted again. This step clarifies the importance of the detection of not only the tip, but the needle angle, since the tip can be in the proper position, but the needle body can be outside the allowable limits.

- If needle was angulated over some preset threshold and the tip was not close to the desired position, the software should prompt and suggest the reinsertion of the needle.

6) If needle reached its final position (e.g. base plane) and the displacement was still within the tolerance limits, the HDR procedure can be performed safely.

Using the proposed automatic needle identification algorithm, the safety step was introduced into the clinical procedure. If the uncertainties about the needle position are identified and quantified, the decision about the future

course of action can be made: the treatment plan can be corrected and recalculated, or the needle can be withdrawn and reinserted again.

III. Results

In our experiments, we were capable of determining the needle-tip position up to 15 times per second. The representative case of the needle identification in the principal step was presented in Fig. 3.

To test the needle detection algorithm for in-plane deflections, we used an ultrasound video stream recorded during the live needle insertion for an existing patient and a frame grabber. The algorithm was able to effectively handle each frame of the incoming stream. The needle detection was achieved in real-time within the limitations of the hardware components. The observed precision of the needle identification was less than 1mm for the needle tip, and less than 0.5° for the deflection angle. The representation of the initial and transformed images following needle identification was shown in Fig. 4. The coordinate system could be associated with the treatment planning system, and consequently, the correction procedure can be improved.

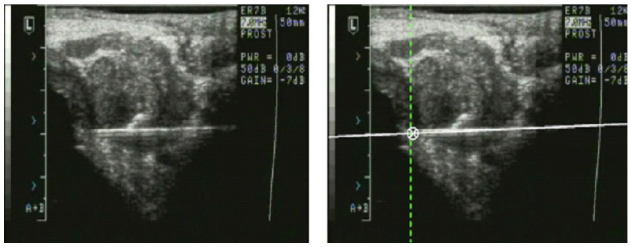

Fig. 4. Typical result of the needle detection algorithm: Left: acquired US image, Right: full line is calculated using modified Hough transform, and dashed line represents predicted position of the needle tip without deflection. Detected needle tip is denoted by "X" mark.

IV. Conclusion

In this article the needle identification algorithm together with its clinical implementation for HDR prostate brachytherapy was proposed. The methodology does not require additional measurements or devices, such as a source detection dosimeter. The needle identification could be included in the clinical procedure using already available resources, such as a treatment planning computer with an additional frame grabber, which will record the US images in a real-time. The proposed algorithm can be run multiple times during the procedure. Consequently, both the prescription dose and the dose to critical structure could be updated in the adaptive manner.

Additional improvements and automation could be reached by the means of motorized US probe driver, and possibly even motorized needle insertion mechanism. Moreover, the proposed algorithm is in no way limited to HDR brachytherapy, and can be easily extended and adopted for prostate LDR procedures, potentially pushing the needle-based brachytherapy procedures into the realm of Image Guided Radiation Therapy (IGRT).

The future work includes developing algorithm for the DICOM-RT images transfer from the needle identification software directly to the treatment planning system with already segmented needles.

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