Automated Treatment Planning for Prostate Cancer HIFU Therapy

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***Abstract* - A framework for computer-assisted treatment planning for prostate cancer high intensity focused ultrasound (HIFU) treatments using 3D ultrasound images, user tracing, and 3D models of the prostate, urethra, and rectal wall was presented previously. This framework provides the input for the current research: the development of a general-purpose HIFU treatment planner module. This module is capable of automatically specifying the prostate HIFU treatment sites using given prostate anatomical information from 3D ultrasound images combined with information on HIFU probes, transducers, and elementary lesion parameters that are stored in a lesion library file. The output of the automatic planner module is a complete treatment plan that is executed after interactive physician review. Additional inputs to this module include clinically relevant parameters, such as inter-lesion spacing and treatment margins. Advantages of this approach include a reduction in the overall treatment time, the ability to easily and accurately plan treatments for complex prostate shapes, and the ability to adapt the planner to other systems and geometries simply by providing a different lesion library specific to that system. The automatic planner module has been integrated into the treatment software of the Sonablate® 500 image-guided HIFU device (Focus Surgery, Inc). The entire treatment planning process is presented, highlighting the usefulness of the automatic planner module.**

Keywords-HIFU, treatment planning, prostate cancer, 3D models, image-guided.

I. Introduction

The work presented in this paper is one component of a much larger effort to radically enhance the physician's capability to plan, review, and execute ultrasound image guided HIFU treatments in general and of prostate cancer HIFU treatments in particular. Figure 1 outlines the overall goal of this effort. This paper concentrates on the dashed blocks.

A. *Current Treatment*

The first step in the treatment of prostate cancer using the Sonablate® 500 (SB-500) is to prepare the system and patient (see Figure 1). A key step in this process is the positioning of the probe with respect to the prostate in order to place the treatment region within the range of the probe. Images of the entire prostate from the bladder neck to the apex including the adjacent rectal wall are obtained. At this point the computer-assisted treatment approach depicted in Figure 1 diverges from the current treatment planning approach.

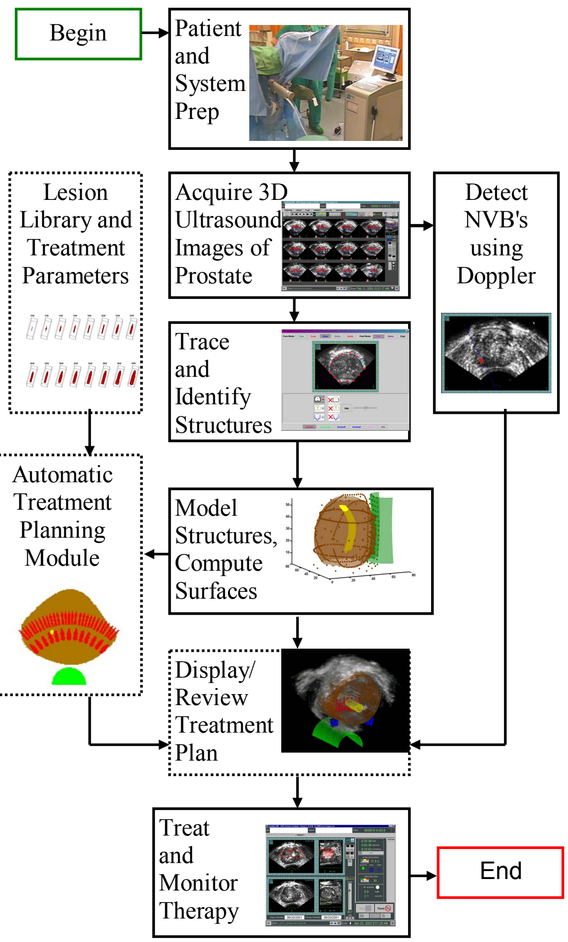

Figure 1. Global HIFU Treatment Planning Flowchart. The Automatic Treatment Planner Module, Lesion Library, and Treatment Plan Display/Review Blocks (dashed) are described in this paper.

Treatment planning for prostate HIFU treatments is currently performed by manually defining treatment zones on sector images that are spaced evenly throughout the prostate [1] The angular extent of treatment site placement in each sector image is defined by the size of the opening within the transrectal probe tip that contains the HIFU transducer.

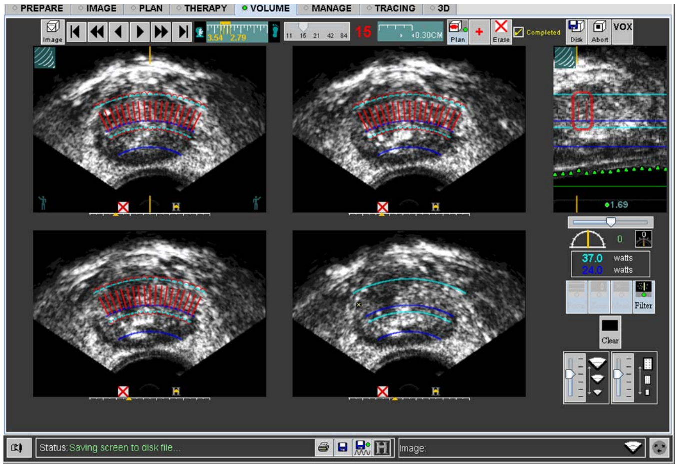

Figure 2. Current treatment planning for the Sonablate®500. The physician marks the extent of the treatment boundreis (red zones in the sector images) in each sector image. The longitudianl image (upper right side) displays the length of treatment from the base to the apex of the prostate.

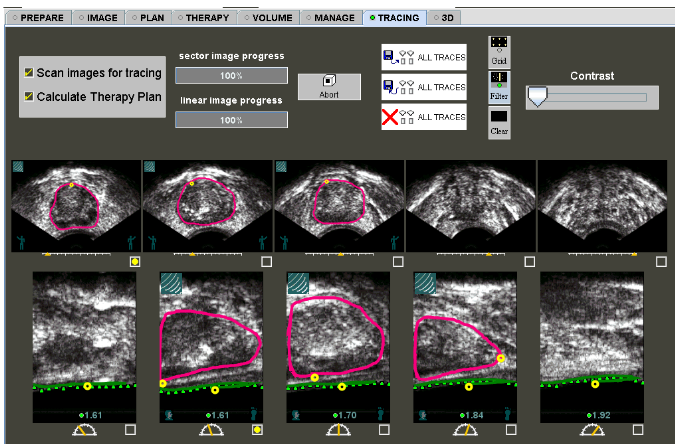

Figure 3. User interface for tracing the anatomical structures. The green line (automated detection) in the longitudinal images is used to outline the rectal wall. The pink outline of the prostate is traced by the physician to indicate the prostate boundary from which the prostate structure is formed.

The physician is shown sector images (transverse slices of the prostate) evenly spaced throughout the gland with a midline longitudinal image of the prostate along the right side of the screen as shown in Figure 2. Within each sector image the physician selects the left and right boundaries of the desired treatment zone for each transducer focal depth as shown in Figure 2. During the planning, the longitudinal image shows the length of the planned treatment. Following the manual treatment planning, the final step is to initiate and monitor the automated treatment following the physician defined plan (bottom block in Figure 1).

B. *Computer-Assisted Treatment*

Following the acquisition of the 3D ultrasound image set of the prostate, the physician traces the boundary of the desired structures (prostate capsule, urethra, etc) as shown in Figure 3. This user input is then used to produce models of the structures that represent the surface of the tissue as per anatomical features. These steps are discussed in detail in [2]. At this point the models, lesion library, and treatment parameters are input into the automatic treatment planning module.

This automated treatment planning approach [3] discussed in this paper is unique in the following ways: (i) it is general-purpose, as treatment plans are based only on the treatment zone geometry and the lesion library elements (which can be added/modified at will), and (ii) it is governed by global treatment parameters, such as treatment margin and treatment site overlap.

II. METHODS

A. *Lesion Library*

The lesion library elements integrate the focal distance, the transducer characteristics, the rectal wall position, and the transmit characteristics (power, frequency, and duration) into a three dimensional matrix representation of a lesion. A library based on simulations [4] of single lesions was created.

The library includes two focal distances (3.0 cm and 4.0 cm) and two rectal wall distances (10 mm and 15 mm). In order to produce lesions of varying size, the total acoustic power was systematically changed. The resulting library contains 54 elements that encompass a range of total acoustic power settings for each combination of focal distance and rectal wall distance. Four elements of the lesion library are shown in Figure 4. The simulation was based on finite-amplitude acoustics for inhomogeneous media coupled with the bio-heat equation to produce each element of the library [4].

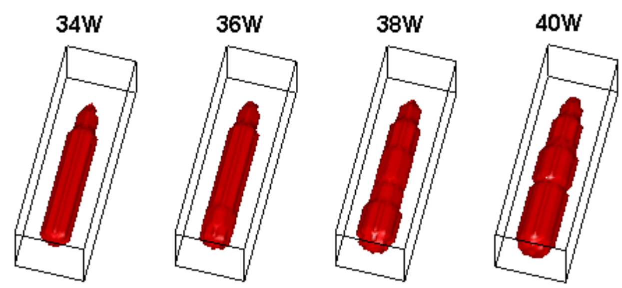

Figure 4. Sample lesion library elements (4 of 54 shown) from the produced by simulation. These elements resulted from a 40 mm focal length transducer with a 15 mm rectal wall location; box is 4x4x12 mm in size. Values are given for the associated total acoustic power.

B. *Treatment Parameters*

The treatment parameters are contained in a property file accessed by the automatic treatment planning module during operation. These parameters control the placement of treatment sites needed to create a full ablation of the prostate. The property file approach permits flexible adjustment of parameter settings. The following are the five parameters:

- Maximum overlap in depth (mm)
- Maximum overlap in transverse directions (percent of element width)
- Minimum overlap in transverse directions (percent of element width)
- Maximum volume fraction permitted outside of the prostate boundary: i.e. treatment margin. (percent of the element volume)
- Maximum Treatment Angle (degrees defined by the opening in the probe tip)

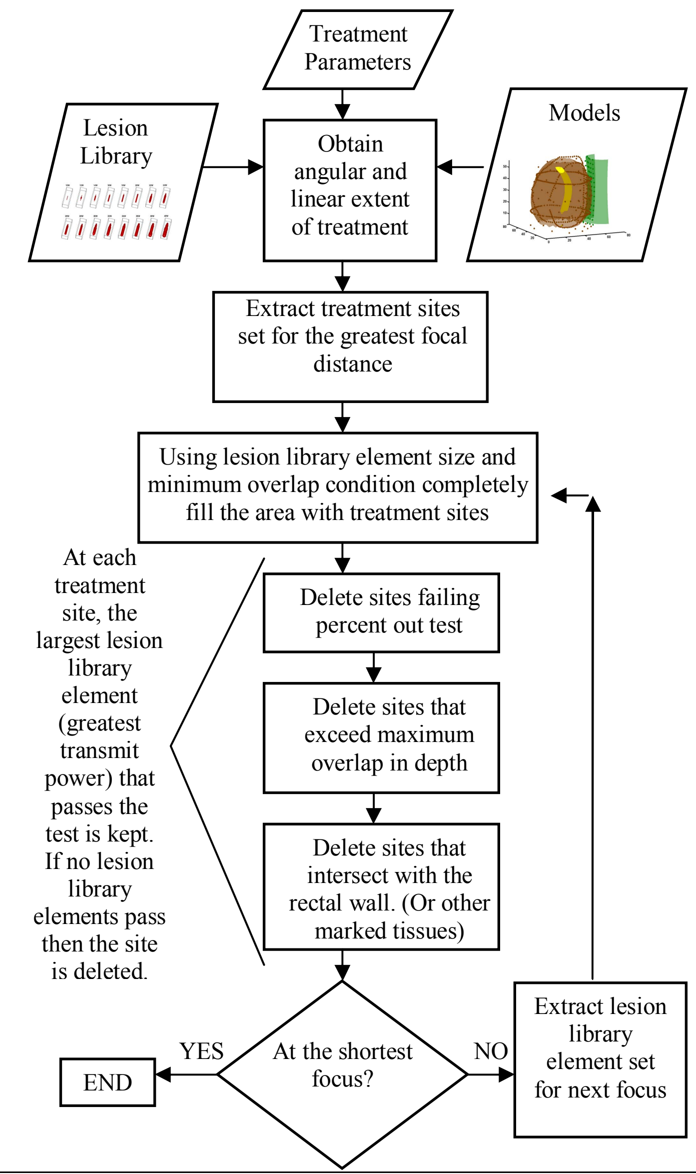

Figure 5. Flowchart for the Automated Treatment Planner Module.

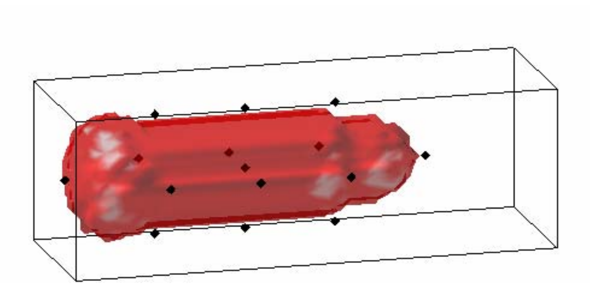

Figure 6. The 15 dots represent the points that are used to determine the percent of the lesion that is outside the prostate capsule. The size of the box is 4x4x12 mm. The lesion is the result of a simulation at focal length of 30 mm with a 15 mm rectal wall location and total acoustic power of 38 W.

These five treatment parameters provide the flexibility to precisely plan a treatment that results in full ablation of the prostate including a margin of tissue surrounding the prostate. The three overlap parameters control the spacing of the treatment sites. The term transverse refers to directions transverse to the depth. The lesion volume fraction value determines the margin to be treated (i.e. extent of the treatment beyond the prostate capsule). The maximum treatment angle defines the extent of rotation permitted by the opening for the transducer within the probe tip.

C. Automated Treatment Planner Module

The automated treatment planner module uses the information contained within the treatment parameters, the models, and the lesion library to create a treatment plan. The key steps of the treatment planning algorithm are given in Figure 5.

The automated treatment planning proceeds for each focal distance within the library by placing as many as possible of the largest lesion library element for the given focal distance and rectal wall distance combination. Next the planner systematically checks each treatment site for the permitted extension outside the prostate, the permitted overlap conditions, and the intersection with any regions that are marked such as the rectal wall or the neuro-vascular bundles (NVBs) found by the NVB module [5]. If any of these tests fail for the initial lesion library element choice, the program tests the next smaller element for the given focal and rectal wall distances until one passes the test or the smallest lesion library element is reached. If the smallest element fails then the site is removed from the treatment plan. This is repeated for each focal distance within the lesion library.

The computation of the percent of the lesion library element that extends beyond the prostate is relatively intensive when compared with the other steps within the automatic treatment planner. In order to minimize this computation time the percent of the lesion library element that extends outside the prostate capsule is estimated using 15 voxels per element. The locations of the 15 voxels for an example lesion library element are shown in Figure 6. Three voxels located on the long axis of the element (1 voxel at the treatment site center and 1 voxel at each tip). One voxel located at the mid point in the depth direction on each external surface along the linear and sector axes (for a total of 4). This placement of 4 exterior samples is repeated at the depths located half of the distance from the treatment site center to each tip (8 voxels). This approach results in a reduction in the processing time by two orders of magnitude compared to a point-by-point computation.

III. RESULTS

All results displayed in this paper used 3D ultrasound data sets gathered prior to HIFU treatment of the human prostate. The computer assisted treatment approach has been implemented in the current SB-500.

The implementation of the computer-assisted treatment within the SB-500 began with gathering the images for the 3D data set. During the tracing step (see Figure 1), the rectal wall is automatically detected. The prostate capsule was traced manually through the interface shown in Figure 3 and the 3D models for the prostate and rectal wall were calculated [2]. These models, the lesion library, and the treatment parameters were used to create the treatment plan shown in Figure 7. This treatment plan permitted 40% of the lesion library elements to extend beyond the prostate gland and resulted in 404 individual treatment sites. The top and the left and right sides of the prostate are free of lesions as a result of the limited treatment library (two focal distances) and the limited extent of treatment in the sector. Treatment of portions of the prostate that are not covered by this plan is achieved through re-alignment of the probe within the rectum.

The results shown in Figure 7 are screen images from the 3D viewing screen that is integrated into the SB-500. This screen permits the physician to toggle ON/OFF visualization of the models, rotate the displayed 3D images using a trackball, and slice the 3D images. This interaction permits the physician to review and interact with the treatment plan before initiating the HIFU treatment.

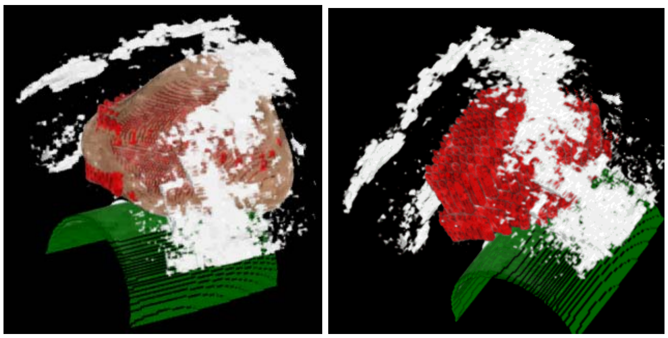

Figure 7. Resulting treatment plan produced by the automated treatment planner that is implemented in the SB-500. Left side shows the model structures for the prostate capsule (brown), the treatment sites (red), and the rectal wall (green). The right side is the same as the left with the prostate capsule hidden.

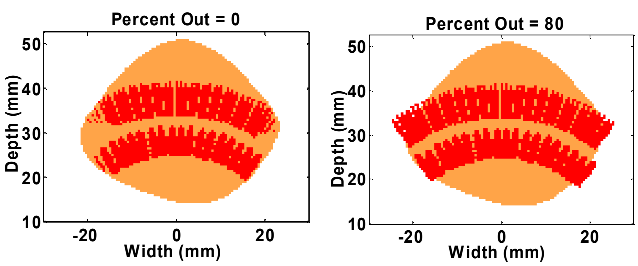

Figure 8. Effect of changing the value of percent out (margin) between 0% permitted (left) and 80% permitted (right). The rectal wall was set at a distance of 10 mm.

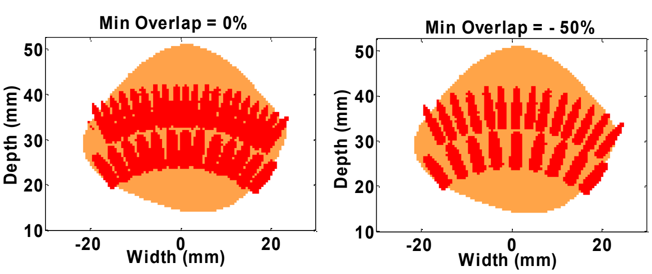

Figure 9. Effect of changing the minimum overlap percentage. Same prostate slice as Figure 8. In this case the rectal wall position was set at 15 mm and the treatment margin was set to 50%.

A series of tests were performed offline on data gathered by the SB-500 with the maximum treatment angle set to 180°. This permits clearer visualization of the effect of changing the other parameters of the treatment plan.

In Figure 8 and Figure 9 the effect of changing the percent of the lesion that may extend beyond the prostate capsule and changing the minimum overlap in the transverse direction are demonstrated. The permitted maximum overlap parameters for both the depth and transverse directions remain unchanged. In Figure 8, the rectal wall was positioned at 10 mm and the minimum overlap in the transverse directions was set to 0% while the percent of the lesion volume that may extend beyond the capsule was set to 0% and 80%. In Figure 9, the lesion volume percent that may extend beyond the capsule was set to 50% and the rectal wall was positioned at 15 mm while the transverse minimum overlap was set to 0% and -50% of the lesion library element width.

IV. Discussion and Conclusions

The results of the automatic treatment planner demonstrate the ability to tailor a treatment plan through the use of the lesion library and 5 treatment parameters. To account for a change in the transducer or acoustic properties, simply updating the lesion library is all that is needed. A more or less aggressive treatment may be accomplished through a simple change in the treatment parameters. These simple inputs into the planner module provide an intuitive approach to tailoring a HIFU treatment plan.

The computer-assisted treatment planning provides tools for the physician to aid in visualizing the treatment of the prostate. This visualization will aid the physician in treating the entire gland and margin as well as avoiding the rectal wall and NVBs. The described method for treatment planning can easily be tailored to the treatment of other organs using other HIFU devices, by only changing the lesion library elements and the treatment parameters.

Acknowledgments

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