COMPARISONS OF NEEDLE INSERTION IN BRACHYTHERAPY PROTOCOLS USING A SOFT TISSUE MODEL

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The success of medical procedures using needles is correlated to the accuracy of the needle insertion in the tissue. The study presented in this paper aims at comparing the results of different prostate brachytherapy protocols concerning needle insertion order and its influence on tissue deformations. Prostate brachytherapy consists in the insertion of radioactive seeds inside the prostate tissue using needles under visual guidance with trans-rectal ultrasound. Depending on the country, hospital and physician, different protocols are used to insert the needles into the prostate. The main difference is related to the order of insertion of the needles. Some protocols perform the insertion of the needles and seeds one by one, checking the position of the seeds with real-time X-ray fluoroscopy at each iteration. Other protocols give priority to the insertion of all needles in a given order and then all the seeds. As prostate and surrounding organs are soft tissues, deformations occur when needles are inserted into the tissues. Independently of factors such as the procedure duration and physician skills, the study of the order of insertion of the needles relatively to the presence and/or location of other needles may give quantitative information about the different deformations undergone by the tissue depending on the protocol. Our comparison study is conducted thanks to a discrete soft tissue model allowing the accurate modelling of needle insertion into soft tissues. Results show that prostatic tissue deformations depend on the protocol used. The ability of soft-tissue modelling methods to compare the consequences of different medical gestures independently of other parameters was also demonstrated through the different simulations.

PROSTATE BRACHYTHERAPY

Prostate cancer is nowadays the most diagnosed cancer among men in developed countries. Over the last ten years, the number of medical procedures to treat this cancer has considerably increased and different options are now possible in function of the cancer staging. The main treatments are radiotherapy and surgery. New promising procedures have been recently developed. Among them, brachytherapy takes an increasing place as it is less invasive than surgery and potentially reduces iatrogenic effects.

The brachytherapy procedure, illustrated in figure 1, consists in introducing radioactive seeds in the prostate through needles. The gestures are conducted with the help of ultrasound imaging acquired by an endorectal probe. Poor quality of images as well as movements and deformations of the tissues (prostate and its surrounding organs) are the main limiting factors of the efficiency and result quality of these interventions. Experienced physicians can only compensate for these deformations. Thus, medical simulators and especially brachytherapy simulators represent an alternative to give a better comprehension of prostate deformations in its anatomical environment and to improve the planning of medical interventions and the training of physicians. Medical simulators can also be used to compare different protocol options and to test them on a given anatomical model. In this paper, the feasibility of the use of a medical simulator as a tool to compare different gestures is studied.

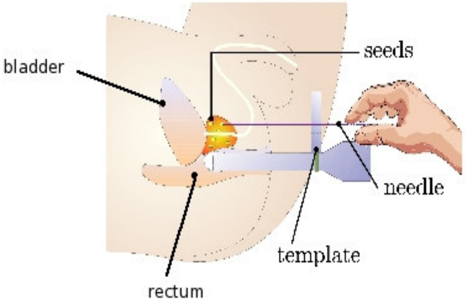


Fig. 1:
Schematic illustration of the prostate brachytherapy protocol. Radioactive seeds are inserted in the prostate (in orange) through needles with the help of an endorectal probe. The bladder and the rectum are the two main surrounding organs.

SOFT TISSUE AND NEEDLE MODELLING

Simulating surgical procedures is still a complex challenge. Modelling methods have to take into account specific geometries and properties of the patient organs and have to achieve some performance criteria like accuracy or real time, depending on the simulator objectives. In the last two decades, different kinds of soft tissue modelling methods have been proposed, often classified as discrete or continuous models [1]. Mass-spring and finite element models are the most common solutions for modelling tissue deformations. Few computer-based training systems focused on the modelling of complex anatomical environment have been developed. Surgical simulators include the complete modelling of a given organ but do not often deal with complex interactions between surgical tools and organs or interactions between organs or tissues.

In this paper, a fully-discrete soft tissue modelling method [2] is used to simulate the prostate in its anatomical environment. The modelling method used in this study is capable of modelling both deformations of organs and interactions with the instruments. It owns a specific formulation of the elasticity, using a volumetric local shape memory. The description of the components of each set of organs allows the user to easily define interactions both with external elements like surgical tools, especially needles, and internal elements like the surrounding organs of the prostate.

The discrete modelling method used in this study allows the simulation of needle insertions into soft tissues too. Simulation and modelling of needle insertion have been studied in 2D and 3D environments for general or particular applications [3]. In our model, different needles can be inserted in the same tissue and the velocity and direction of insertion can be controlled in 3D.

PROSTATE BRACHYTHERAPY SIMULATIONS

A prostate brachytherapy simulator is composed of a complete soft tissue model of a prostate anatomical environment, including the prostate and its main surrounding organs, and the modelling of the main surgical tools, an ultrasound probe and brachytherapy needles. Boundary conditions, tissue geometry and biomechanical tissue properties are of major importance in simulation and modelling applications because these factors affect the amount of tissue deformation, needle deflection and interaction forces. In this study, we will focus on a generic model as an average of existing parameter values to compare different protocols. The introduction of specific patient model will be discussed in the last section.

1. Anatomical environment

The discrete model used in this study allows modelling of intricate anatomical configurations with different soft tissues or organs. The main surrounding organs of the prostate are the bladder and the rectum. Fat tissues are present all around these organs and pelvic bones represent boundary conditions of our model. The shape of the bladder depends on its filling. The volume of this organ can be controlled with our model and its influence will be studied as a factor of tissue deformations. During a brachytherapy, the rectum shape relies on the ultrasound probe position in it. Bad probe positioning can lead to more deformations on prostatic tissue. As an average position, the probe should be parallel to the rectum wall. The positioning of the probe will nevertheless be studied as a factor of prostate deformations in our simulations.

2. Surgical tools

The two main surgical tools in a prostate brachytherapy procedure are the endorectal ultrasound probe and the needles. The probe will be modelled in combination of the rectum modelling.

Concerning needles, the needle force modelling presented in [2] will be used. It consists of three different forces, divided according to the model proposed by [4]: (a) a cutting force exerting by the needle tip in order to move through the tissue; (b) a puncture force to puncture a tissue, which is generally much higher than the cutting force due to the surface tension or the presence of a capsule; (c) a friction force applied along the needle shaft. These forces are computed and applied on the tissue but depends on the type of the needle and its insertion velocity as well as the tissue properties. The reaction forces from the tissue have also to be computed to simulate the movement of the needle. As we are using a discrete model, forces can be applied directly on the particles. Our discrete method does not need any re-meshing stage in order to ensure that element boundaries are present when forces are applied. The needle can thus be inserted in any location of the tissue without extra cost. The insertion of several needles is also possible and allows us to compare different brachytherapy protocols as explained in the introduction.

EXPERIMENTS

Different protocol options have been simulated. The first objective was to observe the influence of needle insertion order on prostate deformations, knowing the number of needles inside the tissue. The influences of different factors such as bladder volume, rectum shape and prostate size have also been studied. A description of the prostate environment is provided in figure 2.

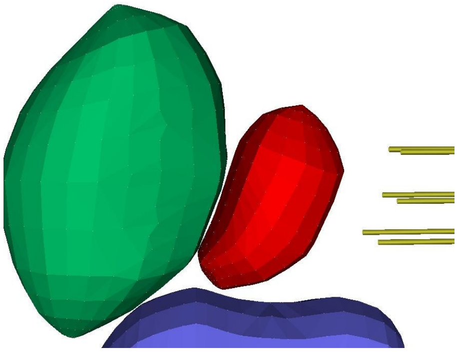


Fig. 2:
Anatomical description of a brachytherapy environment. The prostate (in red) has two main surrounding organs, the bladder (in green) and the rectum (in blue). Fat tissues separate all the organs.

1. Needle configurations

Two main factors can influence the amount of prostate deformations during a brachytherapy. Some protocols commonly used in North America (for example in the British Columbia Cancer Agency at Vancouver, Canada) consist in inserting needles one by one in the tissue, always removing a needle before inserting another one. In an other protocol (which is used in Grenoble's hospital, France), all the needles are inserted before the introduction of the radioactive seeds: needles are inserted in the tissue in the presence of other needles. Two parameters have been studied in our simulations: the position and the order of needle insertion, in function of the needle numbers inside the prostatic tissue.

For the comparisons in this paper, a number of six needles has been chosen. Four different configurations were tested. The insertion points numbering is given in figure 3. Two different insertion orders were tested. Considering the numbering given in figure 3, the first configuration consists in inserting the needle in a clockwise order, following the numbers on figure 3. The second configuration alternates the needle insertion points from the right to the left part of the prostate (following the numbering in figure 2: 1, 4, 6, 3, 5, and 2). These two configurations were simulated with two different conditions: in a first type of simulation, the needles were left inside the tissue (like Grenoble's hospital protocol); in a second type of simulation, the needles were removed out of the prostate after their insertion (like North America's protocol).

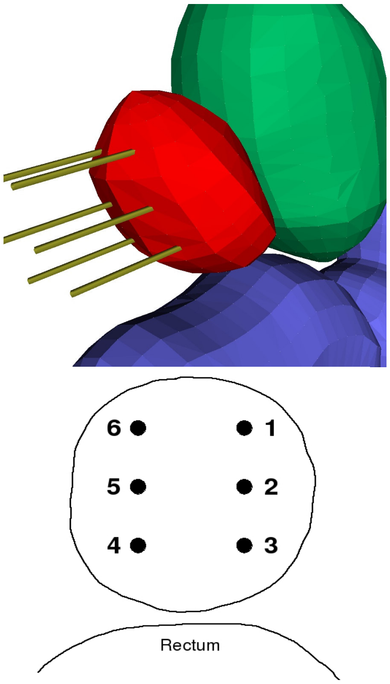


Fig. 3:
Numbering of the needle insertion points: four different configurations were tested.

The four different protocols are:

- Protocol 1: needles inserted in a clockwise order and not removed from the prostate;
- Protocol 2: needles inserted alternatively on the right and on the left part of the prostate and not removed from the prostate;
- Protocol 3: needles inserted in a clockwise order and removed after each insertion;
- Protocol 4: needles inserted alternatively on the right and on the left and removed.

2. Anatomical environment

Different parameters of the prostate anatomical environment have been introduced in our study. The first one is the bladder volume influence, in order to determine if an empty bladder produces more deformations than a full one. The second parameter is the ultrasound probe influence combined to the rectum shape. Bone positions can also be taken as an input parameter. The last parameter is the prostate size. All the simulations have been done by varying the prostate size in order to study its impact on the deformations.

RESULTS

1. Prostate displacements in function of the protocol

First results concern the prostate displacements observed after the insertion of all needles. A summary of the measurements obtained with the four different protocols is given in table 1. The measurements are presented as a relative value and are expressed in percentage (of the prostate size in the direction of insertion). The mean displacements are bigger for the two protocols were the needles are not removed from the prostate (protocols 1 and 2). The prostate displacements are almost negligible when the needles are removed after each insertion. The maximum prostate displacement value for the two first protocols is relatively important. It mainly concerns the middle of the prostate. The spatial distribution of the prostate displacements is illustrated for the four protocols in figure 4. The simulations presented in this paper show the relative importance of the presence of other needles on final prostate displacements. The role of the insertion order is small compared to this first phenomenon.

Results / **Protocol**	**Mean Displacements (Min-Max) (Standard deviation)**
Protocol 1	6.9% (0.4%-33.1%) Std: 6.6%
Protocol 2	6.6% (0.4%-31%) Std: 6.2%
Protocol 3	1.4% (0.1%-4.8%) Std: 1%
Protocol 4	1.6% (0.2%-5.1%) Std: 1.1%

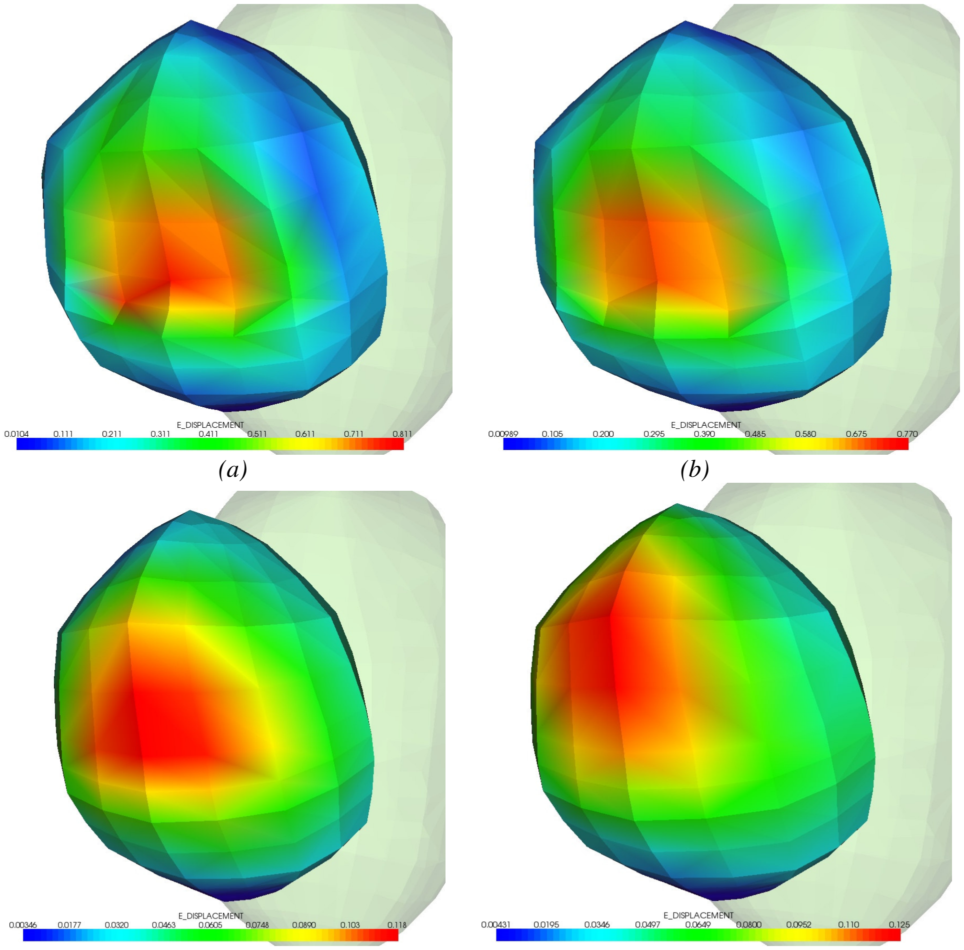
Table 1:
Prostate displacements with the four different protocols: Mean, minimum, maximum and standard deviations are detailed for each protocol. Measurements are given in percentage of the prostate size.

2. Displacements of the insertion points

A second observation concerns the displacements of the insertion points before the insertion of the corresponding needle. Brachytherapy planning and also needle insertion locations are mainly determined before the realization of the gestures. Thus, if needles cause prostate deformations, the insertion of a needle following several previous insertions will give an error in terms of accuracy for the target chosen for the inserted seed. In this paper, the error of the needle insertion (in terms of distance) on each of the six determined insertion points is detailed in table 2 in function of the four different protocols. The distance between the planned and the real insertion localizations is measured before the insertion of the corresponding needle.

Protocol number / **Insertion point number**	**1**	**2**	**3**	**4**
1	0	0	0	0
2	1.4	**6.9**	0.6	3.0
3	**5.9**	1.2	0.9	0.4
4	2.8	0.7	1.3	0.2
5	**7.1**	3.4	**2.7**	2.3
6	0.8	0.8	2.1	0.8

Table 2:
Distance between the planned and the real insertion point positions before the insertion of the corresponding needle. Measurements are given in percentage of the prostate length in the direction of insertion.



(a) *(b)*

(c) *(d)*

Fig. 4:
Prostate displacements for the four different protocols: (a) Protocol 1 and (b) Protocol 2 have the biggest displacements (mean value around 6% of the prostate size with a maximum displacement of 8mm for a prostate size of 2.5cm in the direction of needle insertion) compared to (c) Protocol 3 and (d) Protocol 4 (mean value around 1.5% of the prostate size).

As underlined in the previous paragraph, protocols 1 and 2 cause more displacements on the prostate. The displacements of the insertion points are bigger for the points localized on the middle where different needle insertions can interfere. The displacement of the insertion point increases with the number of insertions for protocols 2 and 4 (needles are alternatively inserted on the right and left). For the clockwise insertion order, the distance between planned and real needle insertion localizations increases too and is relatively bigger for the middle points than for the other points.

3. *Anatomical environment influence*

The discrete model used in this paper allows the modelling of various anatomical configurations. For example, the bladder volume can be modified and its influence studied. The prostate displacements observed are more important when the bladder is empty, the upper part of the prostate being less constraint. The rectum shape, linked to the ultrasound probe position can also influence the resulting prostate displacement by changing the boundary conditions on the prostate: a probe positioned parallel to the rectum wall will induce less prostate deformations.

CONCLUSION

In this paper, a discrete soft tissue and needle insertion model has been used to study the influence of different brachytherapy protocol options on prostate deformations. The ability of a medical simulator to simulate the combinations of different factors as needle insertion order and number, bladder volume or ultrasound probe position was demonstrated. In the experiments presented, the number of needles already inserted in the prostatic tissue plays a bigger role than the needle insertion order. Anatomical environment and surgical tools can also influence the resulting prostate shape and the success of the brachytherapy procedure.

As the discrete model used in the simulations is capable of modelling complex anatomical environment and its interactions with surgical tools, the study was realized with a realistic 3D model. Future experiments will concern patient specific models and physical properties. The organ shapes will be adapted to each patient and rheological parameters can be determined with new promising and non-invasive methods like elastography [5]. Such experiments could lead to a new tool for intra-operative brachytherapy planning.

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