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AN ANALYSIS ON THE PROSTATE DEFORMATION DURING BRACHYTHERAPY NEEDLE INSERTION

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Abstract: *In this paper is presented a theoretical study and analysis regarding the usage of finite elements on deformations of human internal organs (prostate) that emerge at the claim for puncture by brachytherapy needles. Therefore, in medical practice has been observed that at the insertion of thick needles, some of the internal organs are deformed long enough until the moment in which the external tissues are breached. This deformation of the organs can be an important source of error for special procedures, such as those necessary to perform a brachytherapy, causing an uneven distribution of radioactive seeds into the affected organ. Thereat, the present study aims to determine the dependencies between certain factors related to the insertion procedure of brachytherapy needles and the value of the deformation of the organs.*

Key words: brachytherapy, *prostate deformation, MEF analysis*

1. Introduction

Surgical robots, including those intended for the brachytherapy procedure, requires pre-planning operation, before being used for needle placement procedures. Recording the image (image registering) is the process of transforming the images acquired at different moments or with different imaging modalities, in the same coordinate system.

In order to increase the accuracy and quality of the brachytherapy procedure it has been proposed the usage of a dedicated parallel robot, developed at the Technical University of Cluj Napoca, during the CHANCE project, called Para-Brachyrob [11].

This robot is mounted in the operating room, near the table with the patient (Fig. 1).

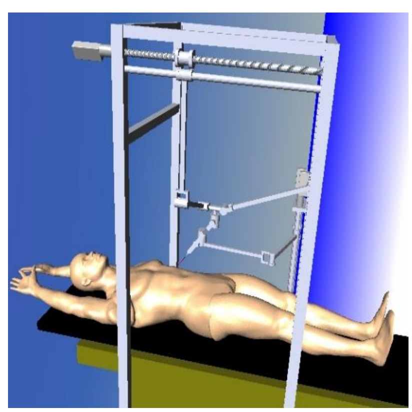

Fig. 1. *Positioning the robot according to the patient*

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In the pre-planning the brachytherapy procedure, used to treat cancer, an important aspect is to identify an optimal approach regarding the choosing of the trajectory of the needles between all the possible ones, established from the geometrical point of view, in order to avoid puncturing vital organs (bones, blood vessels and major organs).

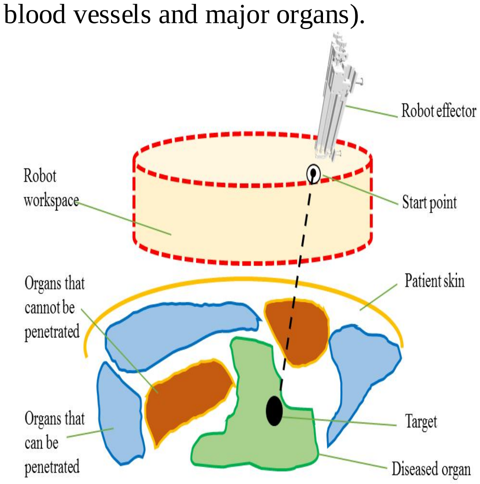

Fig. 2. *Identifying the optimal trajectories*

Taking into consideration the rigidity and high precision of the robotic arms, in comparison with human hands, the robotic systems allow the avoidance of obstacles and significantly adjusting the position and orientation of the needle prior to penetrating the cancerous tissue, and as such, these characteristics improve the access to cancerous tumours.

The trajectories of the robotic effector arm, that allow the needles to target the tumour, are determined for each patient based on the following information: the geometric model of the patient and his position on the operating table; the geometric model and location of the tumour; information regarding the needles used in brachytherapy (length and girth).

Using virtual environment for programming the needles trajectories, it is proposes a safer procedure for robotic brachytherapy, avoiding vital structures and providing an effective insertion of radioactive seeds (Fig. 2).

In this paper is present a special case of an affected organ, namely the prostate. This method assumes that the radioactive seeds are implanted in a patient's prostate using rigid needles with asymmetric tip. Depending on the size and location of the tumor in the prostate, the dosage and positions of the radioactive seeds are determined by a calculation that is performed using a sophisticated computer program (ex. VariSeed 7.0, Varian Medical Systems, https://www.varian.com/).

Following the analysis and the determination of the destination points coordinates regarding the positioning of radioactive seeds, it is proceeded to their insertion using brachytherapy needles.

In the manual procedure, using the guidance grid, the needles are positioned and moved horizontally, the speed and tissue penetration forces (the perineum and prostate) depending 100% on the skill and experience of the physician (Fig. 3).

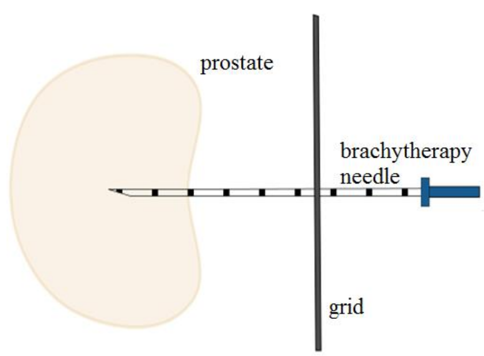

Fig. 3. *The procedure for manual insertion of the brachytherapy needles using the grid [1]*

In the robotic procedure, the needles can be moved on different trajectories, with different values of the speed and penetration forces (Fig. 4).

During such procedures may appear

changes in the positioning of the target from the initial position set by physicist when preparing the operation, depending on many factors, some related to the physiology of the patient, others related to the experience of the physician or the programming of the robot, some depending on the positioning of the equipment and the patient.

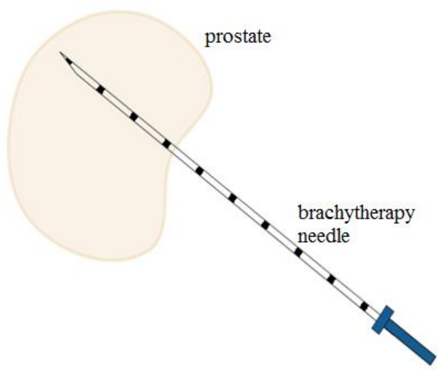

Fig. 4. *The robotic procedure for the insertion of the brachytherapy needles [1]*

These changes occur due to changes in the shape and position of the targeted organ (in this case, the prostate) following the mechanical stresses caused by the forward movement of the needle before penetrating the outer tissues (Fig. 5).

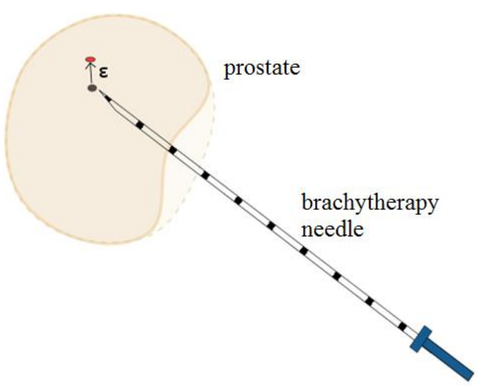

Fig. 5. *Uncontrolled movement of target [1]*

This deformation of the prostate cannot be seen on the screen and, therefore, it is not possible for physicians to counteract this effect. Depending on various factors such as the insertion angle, the needle could bend during the penetration. These two significant effects must be taken into account when planning optimal trajectories.

The optimal solution is not simply the shortest path because it is important for the seed to reach the indicated positions with minimal tissue damage and maximum precision. In a brachytherapy based treatment, the required number of seeds for optimum results varies between 70 and 150, while on a needle can be placed up to 8 seeds. Each new needle insertion will affect the soft tissue, therefore, the aim of the needle trajectory is to place as many seeds as possible [1].

Inserting the needle into the human body is a complex process that involves three main phases:

1. The movement of the needle to the target organ, the contact and the organ deformation;
2. The penetration of the outside tissue of the organ;
3. The movement of the needle inside the organ.

Each of these phases is a complex process from the physical point of view, involving specific phenomena (organ deformation under the pressure of the needle, needle buckling, the friction between the needle and the tissues).

Given the physical - mechanical phenomena during the insertion of the needle, once the tissue is cut by the needle tip, the trajectory of the needle bar is limited to the one created by the advancing of its tip. In the axial direction, however, the needle encounters friction forces due to the adherence of the tissue on the surface of the cylindrical bar.

In addition to the frictional forces, the power required to cut the tissue at the tip of the needle implies an additional penetration resistance force. Consequently, a model of axial force is used if each type of tissue can be parameterized for a particular needle size / geometry by two constants: the friction on the shaft surface and the peak force necessary to cut the tissue (Fig. 6) [2].

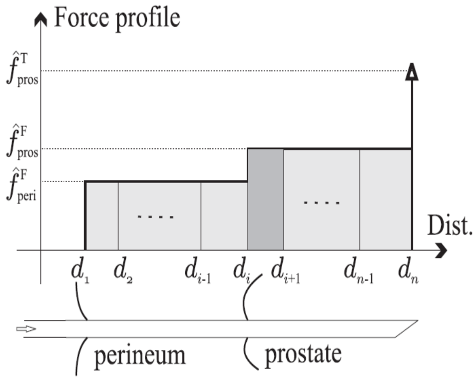

Fig. 6. *Penetrated layers of tissue [2]*

The brachytherapy needles have a bevel in the sharp area to enable them to be more easily guided in different directions to avoid the interference with the pubic arch, thus can be generated trajectories that avoid the pelvic bone (Fig. 7).

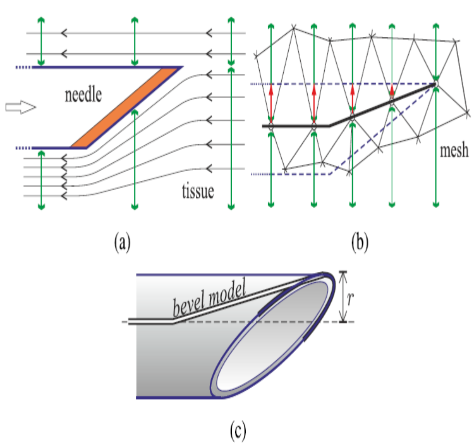

Fig. 7. *(a) The progress of the bevelled needle tip inside tissue; (b) mesh nodes sliding in 2D along a unidimensional tip-bevel model; and (c) tip bevel model in 3D [2]*

The oncologist may also use another direction of the needle by changing procedure plan to target a seed to a location that does not align exactly with a hole in the grid.

Oncologists periodically checks the position of the needle tip during the insertion in the cross-sectional based on ultrasound methods. If the needle advances in a wrong direction, it is withdrawn (partially) and then reintroduced with the rotated tip to correct this error. Therefore, the modelling of the conical tip is relevant to the brachytherapy operation [2].

2. Methodology

It is considered that the deformation of the organs corresponding to phase 1 is an important phenomena that must be taken into account. Further is presented an analysis based on the Finite Element Method (MEF) which aims to determine the correspondences between the stress and deformations in order to optimize the methods of inserting needles.

For this analysis was used CATIA module MEF program.

The 3D model of the patient's prostate was reconstructed based on DICOM files saved in the format of 3D representation VisualisationTool Kit (*.vtk) of the 3D Slicer program. To achieve the analysis based on the Finite Element Method, the procedure shown in Fig. 8 was followed, where are presented even the details regarding the file types used.

The prostate is considered to have an isotropic behaviour. Young's elasticity modulus that can be determined practically, according to the literature has the value of 55-62 kPa. It will be used an average value of 60,000 N/m2 [3], [4].

On this model were used distributed forces, with circular surfaces support that simulate the contact between the needle tip and the prostate. Several analyzes were

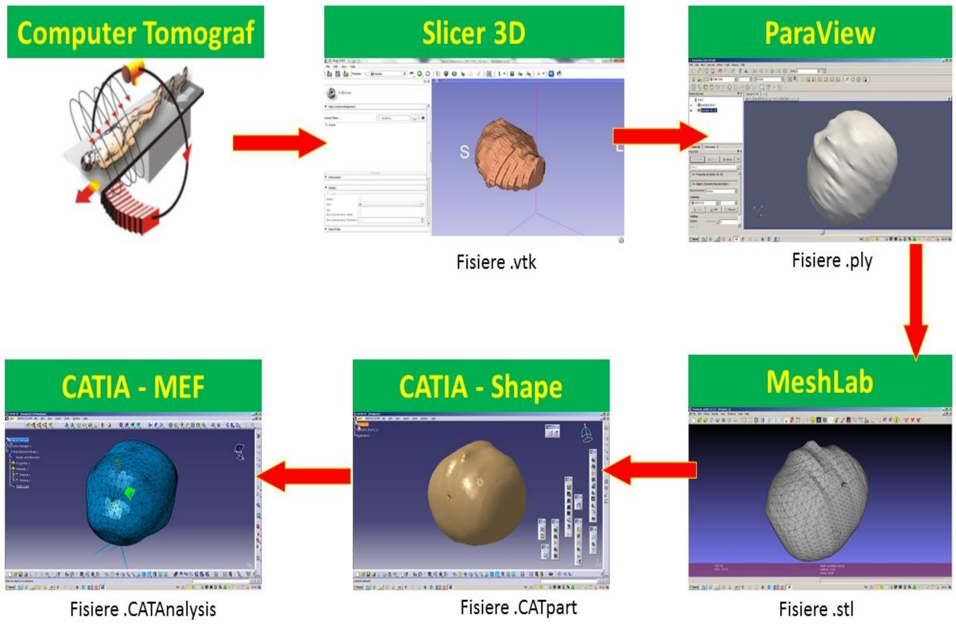

Fig. 8. *The methodology for the analysis using MEF*

conducted using force of 10 N, value often used in literature and considered to be a normal force for the action of tissue penetration [6].

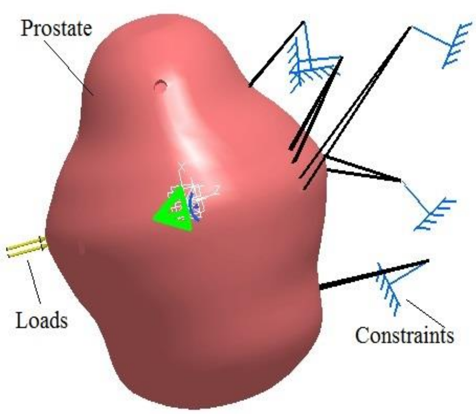

Fig. 9. *The analyzed model*

The angles of penetration into the prostate, as well as the insertion area have been modified (there were considered three areas of penetration: central, lateral, top). The analysed is shown in Fig. 9.

Inside the human body, the prostate is found in direct or indirect contact with adjoining organs (the bone in the pelvic area, bladder, intestines) which behave differently. Therefore, a real simulation of the links between organs is a very difficult process.

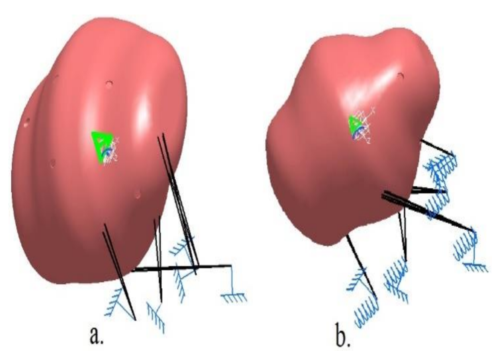

Fig. 10. *Propping the prostate: (a) rigid virtual items, (b) virtual elastic elements*

In this experiment, two cases were simulated: the links between internal organs were fixed through virtual rigid items or through virtual elastic elements.

To achieve these constraints regarding the fastening, several small circular areas were generated outside the prostate and several other points in space that simulates the human body organs. They were connected via the virtual rigid and elastic elements (Fig. 10).

In Fig. 11 is presented the visualizing mode of the analysis results with MEF using CATIA.

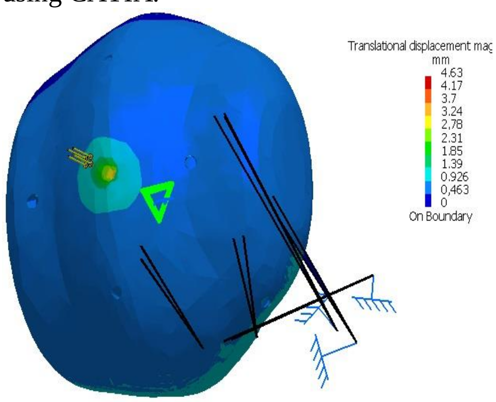

Fig. 11. *Analysis of deformations and displacements occurred when inserting the needle*

The deformation of the prostate can be identified directly on the graphical user interface of the analysis software (Fig. 12), and using the analysis reports.

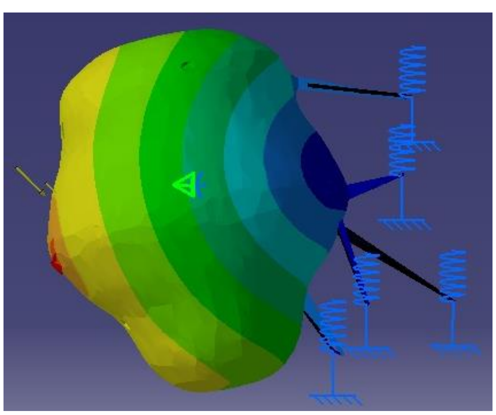

Fig. 12. *Symbolizing the values of deformations*

3. Results

Variation in prostate deformations depending on the location of the needle insertion point towards the geometric centre can be observed in Fig. 13.

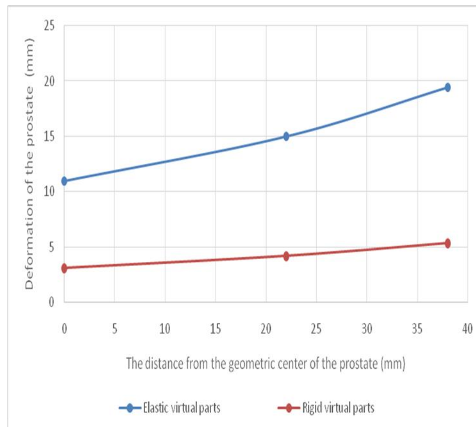

Fig. 13. *Deformation of the prostate depending on the penetration area*

Variation in prostate deformations depending on the angle of incidence of the needle with the surface of the organ is presented in Fig. 14.

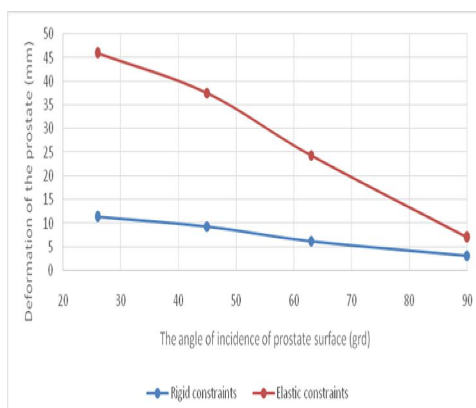

Fig. 14. *Deformation of the prostate depending on the angle of incidence of the needle*

It can be observed that the deformation

values increase with needle deviation from the normal to the surface of the prostate (if prostate is considered a sphere, it is taken into account the deviation from the radial direction).

In Fig. 15 is presented the variation of prostate deformation depending on the value of the pressing force, taking into account the assumption that the needle does not penetrate the outer tissues.

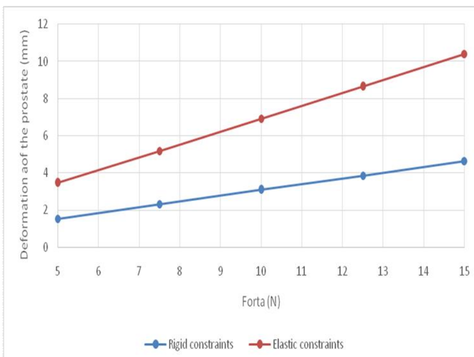

Fig. 15. *Deformation of the prostate based on the value of the pressing force*

4. Conclusions

Inserting the needle into biological materials can determine the rupture and propagation of unstable fissures. It was demonstrated that the deformation and damage brought to the penetrated tissue could decrease with a higher speed of the needle. Quick needle insertions may be used to increase the accuracy of the needle trajectory and reduce tissue damage [5].

The results of the conducted experiments emphasize that the deformation of the prostate can be minimal as long as tree parameters are taken into consideration: the area in which the needle makes the penetration, the angle of incidence of the needle and the pressing force of the needle used to perform the brachytherapy.

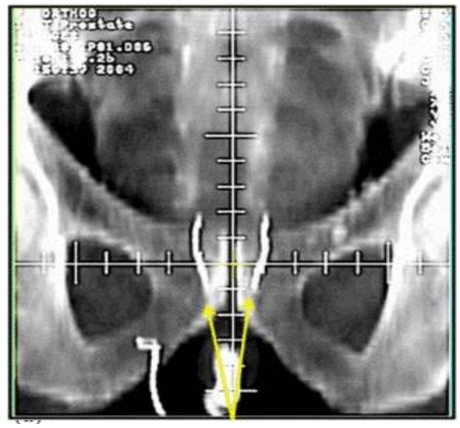

Fig. 16. *Using anchors for attaching the prostate 8*

The study carried out can conclude that the insertion of needles using the robot must occur with the prostate fixation with special equipment (anchor) in order to maintain the positions of the target points (Fig. 16). Researches in this area are presented in [8], [9], [10].

Acknowledgements

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