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Robotic Systems for Prostate Cancer Brachytherapy (Robot-Assisted Systems)

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Abstract

In this review the issues of robotic automation for prostate cancer brachytherapy procedure are studied. The main goal of the brachytherapy robotic automation is to improve the effectiveness of treatment which is achieved, primarily, by means of precise location of the radioactive seeds in accordance with the operation plan. The existing robot-assisted systems used for executing brachytherapy under visualization control (ultrasonic scanning, MRI, CT), their advantages and disadvantages are considered. The main directions for developing the robotic automation for brachytherapy are formulated. The article represents the first domestic review of the literature, dedicated to the issue of robotic automation in brachytherapy for the patients suffering from prostate cancer.

Keywords: Brachytherapy, Prostate Cancer, Robot-Assisted System

1. Introduction

Prostate cancer is the forth frequent cause of death among men[1]. At the initial stage of the disease development the principle methods for curing the prostate malignant tumors are the external directed radiation, surgical method and brachytherapy[2]. Brachytherapy is a method of introducing special microseeds with the radioactive isotope directly into the tumor by means of the needles[3].

There is a standard procedure of implanting the radioactive seeds on the tissue of the prostate[4]. The coordinate grid template is installed on the specialized step-type device, and the needles are inserted through the openings of this grid template (Figure 1).

In the case when the pre-operational planning is done, all the cutoffs are checked for their conformity with the images, used in the process of planning. Then, in two openings of the microseed implantation grid, which are free according to the pan, two fixing needles are introduced, designed for reducing the prostate displacement under the effect of the implantation needles. The needles are implanted manually (Figure 2). The seed bearing needle insertion depth can be controlled either by means of ultrasound in sagittal scanning plane or by means of roentgenoscopy.

When the needle has been drawn through the corresponding opening in the coordinate grid, and the tip of the needle appears at the plane of scanning, a bright point ("flash") appears on the display, because the tip of the implantation needle has the echogenicity marking. This should either coincide with the corresponding coordinate of the seed location according to the implantation plan, or it should be distanced from the seed by not more than 1–2 mm.

On the whole, one can say that the existing procedure of executing brachytherapy has the following disadvantages:

- Low precision of microseeds positioning in the cross direction of the template;
- Low precision of determining the needle insertion depth with the supported measuring bar, which is partially compensated by the availability of ultrasonic scanning;
- Lack of accounting for deformation impact, for rotation and displacement of the tumor tissue and the prostate when the needle is inserted;

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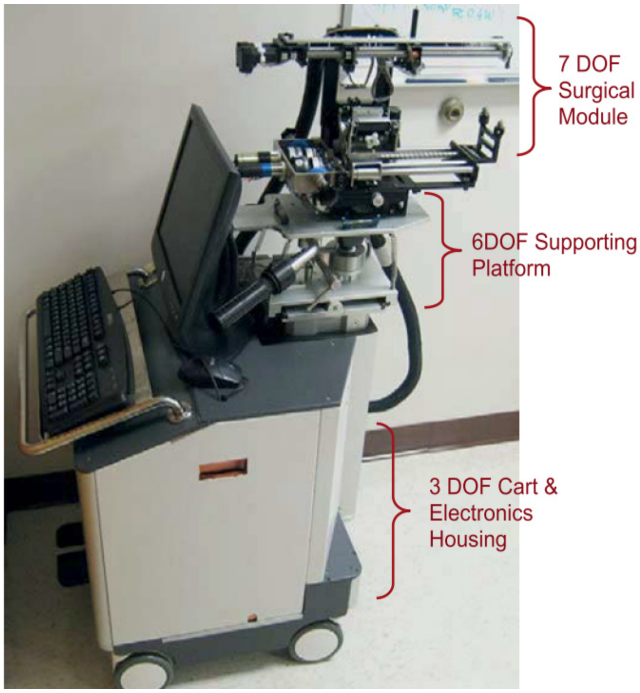

Figure 1. Robot for brachytherapy EUCLIDIAN: surgery module, supporting platform and electronics housing.

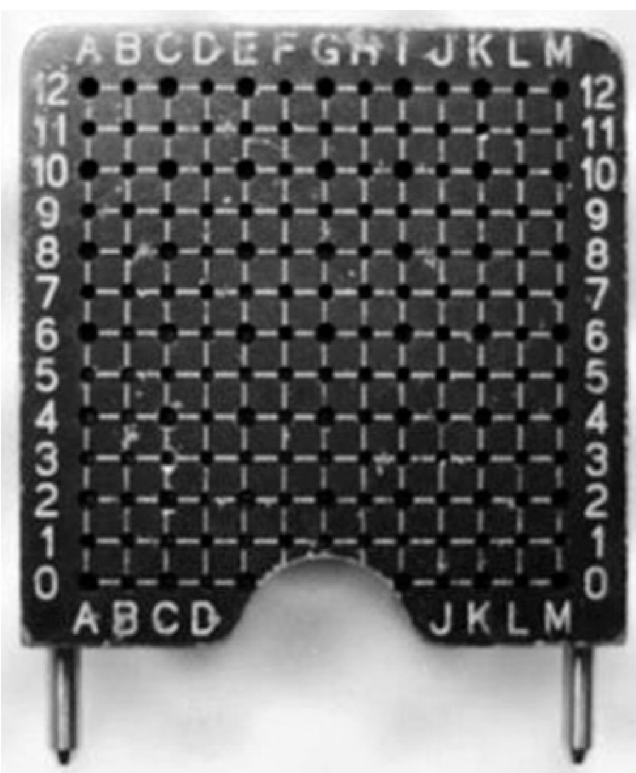

Figure 2. Example of the grid for introducing the microseeds.

- The need for a doctor to be close to the radiation sources during all the time of the procedure;
- Lack of possibility to bypass the natural obstacles in the patient's body (pelvis bone structures, presence of the critically important tissues situated in the vicinity);
- Impact of the method variations, of the operator's level of practice and experience, of human factor on the effectiveness of the procedure.

The most perspective direction of brachytherapy development to seriously improve the efficiency and the results is represented by robotic automation of the procedure, applying the robot-assisted technical systems at all stages of the procedure[5–7]. The principal idea of this approach is replacing the human operator with a robot, which will independently execute all the required activities of the procedure.

Historically the robotic automation in brachytherapy procedure was, probably, for the first time applied in the beginning of 1980-s, when the first microseeds implanting systems appeared, equipped with servo drives[8]. In 2001 D. Elliott and the co-authors proposed a system equipped with an automatic 3 dimension moving device and a microseeds cartridge[9]. In 2002 G. Fichtinger and the colleagues announced the fact of creating the robot-assisted system, possessing 7 degrees of freedom and equipped with Computer Tomograph (CT)[10]. In 2004 Z. Wei and the co-authors suggested using the commercially available industrial robot[11] for brachytherapy. Similar suggestion was voiced based on the results of one more study[12].

The robot-assisted systems acquired their further development in 2005, when a new feature appeared, enabling the needle inclination at a random angle with automatic positioning of radioactive microseeds[13]. In 2006 H. Bassan and the co-authors proposed a modified system, which had the possibility to rotate the needle in the course of insertion and was operated under the ultrasonic scanner control[14]. The system was also equipped with the force and the moment sensors, due to which the feedback chain was established. In 2010 a system was proposed, which allowed for inserting up to 16 needles simultaneously[15] in the prostate.

2. Investigation Concept

A whole series of studies have been dedicated to implementing different types of brachytherapy visualization systems, such as, ultrasonic scanning, Magnetic Resonance Imaging (MRI), CT, roentgenoscopy. This is due to the fact that the quality of visualization during brachytherapy is the most essential in determining the quality of executing the procedure. The example of an experimental robot-assisted device for brachytherapy employing ultrasonic scanning visualization is described in the study by G. Fichtinger and the co-authors[16]. This unit consists of a robot, which moves the needle with the microseeds in space, under control of an ultrasonic sensor. When practiced on a special dummy, the device proved the possibility and the technical viability of the brachytherapy method, but also required considerable updating of the operating robot and the needle position control system. The main drawback to the system was that after implanting each of the capsules the empty needle had to be completely removed from the patient's body and had to be replaced with the new one with the installed capsule. The important conclusions drawn from the study were justifying the necessity to develop the deformation models for different parts of body to position the microseeds in the patient's body more precisely under conditions of the tissue deformation and movement in the process of the implant insertion, as well as the necessity to control the force of the needle insertion to minimize extra traumas of the patient's internal organs.

Robot automation in brachytherapy brings solutions to the tasks as follows[17]:

- Narrowing down the tolerance of positioning the microseeds in the tumor;
- Repeatability of the procedure results;
- Reducing the possibility to damage the critically important organs and tissues;
- More effective radiation distribution in the tumor;
- Reducing the human factor effect on the operation results;
- Decreasing detrimental effect of radiation on medical personnel;
- Ease of training and practicing the technique.

Basic functional requirements to brachytherapy robot-assisted systems are as follows[17]:

- Prompt and easy disconnection in case of emergency;
- Possibility to turn back to the usual manual method of brachytherapy at any time;
- Improving the methods to immobilize the prostate;
- Correcting the operation plan based on the results of the steps already accomplished;
- Possibility for a doctor to study and to approve of brachytherapy plan before inserting the needle;
- Confirming each microseed position and the tip of the needle position with the help of selected visualization method;
- Feedback actuated automated needle control;
- Ease of executing the operation and safety for the patient and the personnel;
- Possibility to clean and to disinfect the robot-assisted system.

As of today, there are 13 robot-assisted systems for brachytherapy in the world, 12 of them are designed for prostate cancer brachytherapy[17]. Some of them possess high degree of self-regulation in inserting the needles for brachytherapy and in implanting the microseeds in automated mode. These procedures are implemented under control of an experienced doctor. All existing systems, except that of manufactured by FIRST, Elekta-Nucletron (Sweden), allow for turning down the practice of using the grid template, which improves the insertion maneuverability of the needle and potentially helps improving the precision of implanting the microseeds. Some of the existing 13 robot-assisted systems could be used for both low-dose and high-dose rate brachytherapy. It also stands to reason that only 3 of 13 systems have been approbated in clinical investigations for the patients suffering from prostate cancer. Some of the existing robots for brachytherapy are described below.

2.1 Elekta-Nucletron FIRST System

The system includes the computerized system of transrectal 3D ultrasonic scanning, robot-assisted device for implanting the microseeds and the system for operation planning named "OncentraSeeds"[18]. Elekta-NucletronFIRST performs the microseeds implantation in real time mode by means of manual insertion of the needles with the help of the operation planning system which enables altering the microseeds position at any moment in the process of their location. The precision of microseeds implanting for his system amounts to ca. 1 mm.

2.2 EUCLIDIAN (TJU) System

This robot-assisted system, developed by the staff of Radiation Oncology Department at Thomas Jefferson

University (USA), consists of five basic modules: manipulator of the transrectal ultrasonic probe with two degrees of freedom, gantry robot with two degrees of freedom, device for inserting the needles with two degrees of freedom, positioning module with six degrees of freedom and a cart with electronics housing with three degrees of freedom (Figure 3)[19,20]. All movements, performed by the surgery module of the system, are assisted by the motors, equipped with high-resolution optical sensors and with gear-boxes. The transrectal ultrasonic probe can move and rotate either in automated mode or under control of an operator, and it affords obtaining he images with the minimal discretion of 0.1 mm. The device for stabilizing the needles for brachytherapy within EUCLIDIAN system makes it possible to orientate the needle at any angle in both sagittal and coronal planes, which improves the stability of the prostate in the course of the procedure[21].

Also, within EUCLIDIAN there is a device, enabling rotation of the needles, which reduces the force required for inserting them and which could potentially lessen the prostate deformation and displacement[22,23]. The precision of locating the microseeds during phantom investigations was within the range of 1 mm.

2.3 UW Robot

There is one more robot for brachytherapy with ultrasonic scanning control, which can be employed for automated and semi-automated positioning of the microseeds[13,24]. In its existing configuration the robot has 6 degrees of freedom and consists of three linear and three rotor slides, and of the device with rotating needles. The important and distinctive features of UW robot are the angles of inclination of the needles (ca. ± 30°), rotation of needles around the longitudinal axis and the variable force of the needle insertion. The precision of implanting the microseeds, according to the results of phantom investigations, amounted to 1 mm[25].

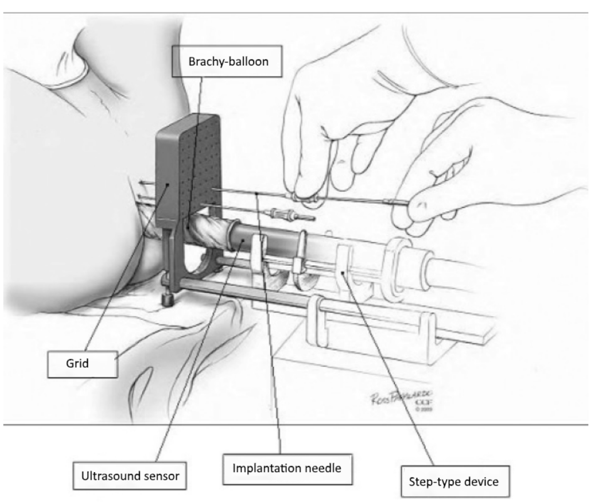

Figure 3. Sketch of the procedure of implanting the microseeds in the prostate.

2.4 UMCU Robot

The robot was developed by the researchers from the University Medical Centre of Utrecht (the Netherlands). Its key feature, distinguishing it among the previous systems, is that it affords executing brachytherapy under MRI control[26,27]. The robot is placed within MRI scanner at 1.5 T. Transrectal ultrasonic scanning, employed in the robotic systems described earlier, has some restrictions, namely, it causes different deformations in the anatomic structure of organs, and the results thereof are effected by poor quality of the pictures due to either its insufficient contact with the mucous tunic or the presence of faeces in the patient's rectum[18]. MRI can overcome such restrictions, and it affords obtaining 3D images with better resolution, as compared to ultrasonic scanning, especially for the soft tissues. It was suggested initially that MRI should be used for dosimetric planning in brachytherapy, as MRI improves visualization of the prostate, of its structural elements, of the surrounding tissues, and, most importantly, of the tumor lesion focus[28].

2.5 JHUMrBot

This robot has 4 degrees of freedom for executing transperineal procedures on the prostate; it is MRI compatible[29,30]. The specific feature is that the system employs a new type of motor, developed specifically for the robot's tasks, the pneumatic step-type motor PneuStep®. The mechanism for implanting the microseeds for the low-dose rated brachytherapy consists of MRI compatible needle injector and of MRI incompatible elements, attached to the control pulpit. The dog tests showed that the average fault rate in inserting the needles and in locating the microseeds under visualization of 3 T MRI amounted to 2 and 2.5 mm accordingly[30]. In turn, the precision of implanting the microseeds was studied with the agar (gel) models, and amounted to app. 1.2 mm with the standard deviation of 0.4 mm, which exceeds the corresponding values for the robotic system discussed earlier[29,30].

Notwithstanding some advantages, executing the robot-assisted operations at the prostate is associated with a number of difficulties. The prostate is a soft tissue organ, which alters its shape and moves when perforated and put under pressure. The gland is surrounded by several anatomic structures (urinary bladder, rectum, neurovascular fascicles), which should not be touched and should be bypassed. The analysis of the movement sequence at implanting the microseeds showed that this process includes not only positioning and orientation, but also rotation, counter-rotation and movement of the needles and of the needle monitoring probe[31]. All this testify to the advisability of using in brachytherapy the open-circuit systems (tele-manipulators and manually controlled robots), where the doctor can monitor continuously how the prostate moves, deforms or swells in the course of implanting the microseeds.

Summarizing the conclusions of reviewing the existing systems, it should be noted, that the principal objective of all suggested developments is improving the effectiveness of the procedure, and this can be achieved, first of all, by means of more precise positioning of the microseeds in accordance with the operation plan. The tolerance of the radioactive microseeds positioning, achieved in the existing robot-assisted systems, is about 1 mm. There are systems existing already, in which some of the functions are partially automated.

3. Discussion

The above-mentioned systems either have been or are being developed in the USA and in European countries. Unfortunately, the activity of Russian authors and developers is drastically insufficient, given the complex of the tasks set in front of domestic public health service in the area of executing brachytherapy procedures. Today in Russia the level of robotic automation in brachytherapy procedures is extremely low, which affects the effectiveness of the patient's treatment negatively. The authors believe that the prospects of developing the robot-assisted systems for the prostate cancer diagnostics and treatment by brachytherapy method are exceptionally extensive. Some of the basic directions are mentioned below:

- Creating the robots capable of controlling the movements of the needles;
- Robotic automation of scanning and visualizing systems;
- Integrating robot-assisted technical systems with the control systems to obtain completely automated systems with remote computerized control;
- Investigating the interaction of the needle with tissues and developing mathematical models of such interaction;
- Investigating the possibilities of applying the flexible needles and developing the mathematical models of their movement.

The most important practical aspect at implementing the robot-assisted systems is the human-robot interface. The effectiveness of the operation and, to be more precise, the effectiveness of the human-operator using all the potentialities of the robot under his control is dependent on this component in many respects.

4. Conclusion

Thus, developing the robot-assisted systems for brachytherapy can afford overcoming the constraints and eliminating the disadvantages of the methods presently practiced in this operation, which will improve treatment results and step up the life standards of the patients suffering from prostate cancer.

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7. References

1. Rodney S, Shah TT, Patel HR, et al. Key papers in prostate cancer. Expert Rev Anticancer Ther; 2014; 14(11):1379–84.

2. Scardino P. Update: NCCN prostate cancer clinical practice guidelines J Natl Compr Canc. Netw; 2005; 3(1):29–33.
3. Yan K, Podder T, Buzurovic I. Radioactive seed immobilization techniques for interstitial brachytherapy. International Journal of Computer Assisted Radiology and Surgery; 2008; 3:165–71.
4. Kuznetsov MA, Ksenofontov AI, Narkevich BY. Brahiterapiya raka predstatelnoy zhelezy s ispolzovaniyem zakryityh granulnyh ragionuklidnih istochnikov [Prostate cancer brachytherapy with the closed type granular radioactive seeds] – Meditsinskaya fizika; 2009; 4:91–104 [in Russian].
5. Cleary K, Nguyen C. State of the art in surgical robotics: Clinical applications and technology challenges. Comput Aided Surg. 2001; 6:312–28.
6. Long JA, Hungr N, Baumann M, et al. Development of a novel robot for transperineal needle based interventions: focal therapy, brachytherapy and prostate biopsies. J Urol. 2012; 188:1369–74.
7. Taylor RH, Stoianovici D. A survey of medical robotics in computerintegrated surgery. IEEE Trans. Rob. Autom; 2003. 19: 765–781.
8. Holm HH, Pedersen JF, Hansen H, Stroyer I. Transperienal 125I iodine seed implantation in prostatic cancer guided by transrectal ultrasonagraphy. J Urol. 1983; 130:283–6.
9. Elliott DM, Berkey JJ. Automated implantation system for radioisotope seeds. United States patent 20026869390B2. 2002.
10. Fichtinger G, DeWeese TL, Patriciu A, et al. System for robotically assisted prostate biopsy and therapy with intraoperative CT guidance. Acad Radiol. 2002; 9:60–74.
11. Wei Z, Wan G, Gardi L, et al. Robot-assisted 3D-TRUS guided prostate brachytherapy: System integration and validation. Med Phys. 2004. 31:539–48.
12. Song DY, Burdette EC, Fiene J, et al. Robotic needle guide for prostate brachytherapy: Clinical testing of feasibility and performance. Brachytherapy. 2011; 10: 57– 63.
13. Meltsner MA, Ferrier NJ, Thomadsen BR. Design and quantitative analysis of a novel brachytherapy robot. Med Phys. 2005; 32:1949.
14. Bassan H, Patel RV, Moallem M. A novel manipulator for prostate brachytherapy: Design and preliminary results. Proceedings of the IFAC Symposium on Mechatronic Systems, Heidelberg, Germany. Frankfurt: Elsevier; 2006. p. 30– 5.
15. Podder TK, Buzurovic I, Yu Y. Multichannel robot for image guided brachytherapy. IEEE International Conference on Bioinformatics and Biomedical Engineering (BIBE); Philadelphia, PA, New York: IEEE; 2010. p. 209– 213.
16. Fichtinger G, Burdette EC, Tanacs A, et al. Robotically assisted prostate brachytherapy with transrectal ultrasound guidance – Phantom experiments. Brachytherapy. 2006; 5:14–26.
17. Yu Y, Podder TK, Zhang YD, et al. Robotic system for prostate brachytherapy. Comput Aided Surg. 2008; 12:366–70.
18. van Gellekom MP, Moerland MA, Wijrdeman HK, et al. Quality of permanent prostate implants using automated delivery with seed: Selectron versus manual insertion of RAPID strands. Radiother Oncol. 2004; 73:49–56.
19. Dev SR, Dev S. Robotics Technology and Flexible Automations. 2nd ed. New Delhi: Tata McGrawHill; 2010. p. 427.
20. Podder TK, Buzurovic I, Huang K, et al. Reliability of EUCLIDIAN: An autonomous robotic system for image-guided prostate brachytherapy. Med. Phys. 2010; 38:96–106.
21. Podder TK, Sherman J, Rubens D, et al. Methods for prostate stabilization during transperineal LDR brachytherapy. Phys Med Biol. 2008; 53:1563–79.
22. Meltsner MA, Ferrier NJ, Thomadsen BR. Observations on rotating needle insertions using a brachytherapy robot. Phys Med Biol. 2007; 52:6027–37.
23. Podder TK, Clark DP, Fuller D, et al. Effects of velocity modulation during surgical needle insertion. Conf Proc IEEE Eng Med and Biol Soc; 2005. p. 5766–70.
24. Meltsner MA. Design and optimization of a brachytherapy robot [PhD thesis]. Department of Medical Physics, University of Wisconsin–Madison; 2007.
25. Meltsner MA, Ferrier NJ, Thomadsen BR. Performance evaluation and optimization of a novel brachytherapy robot. Med. Phys; 2006. 33: 2264.
26. Lagerburg V, Moerland MA, Seppenwoolde JH, Lagendijk JJ. Simulation of the artifact of an iodine seed placed at the needle tip in MRI-guided prostate brachytherapy. Phys Med Biol. 2008; 53:59–67.
27. Lagerburg V, Moerland MA, van Vulpen M, Lagendijk JJ. A new robotic needle insertion method to minimize attendant prostate motion. Radiother Oncol. 2006; 80:73–7.
28. Penner EA. Interventional MR with a mid-field open system. In: Debatin JFAG, editor. Interventional magnetic resonance imaging. Berlin: Springer-Verlag; 1998. p. 11–8.
29. Stoianovici D. Multi-imager compatible actuation principles in surgical robotics Int J Med Robot. 2005; 1:86–100.
30. Stoianovici D, Song D, Petrisor D, et al. MRI Stealth robot for prostate interventions. Minim Invasiv Ther Allied Technol. 2007; 16:241–8.
31. Sridhar AN, Hughes-Hallet A, Mayer EK, et al. Image-guided robotic interventions for prostate cancer. Nat Rev Urol. 2013; 10:452–62.