Accuracy of needle implantation in brachytherapy using a medical AR system – a phantom study

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ABSTRACT

Brachytherapy is the treatment method of choice for patients with a tumor relapse after a radiation therapy with external beams or tumors in regions with sensitive surrounding organs-at-risk, e. g. prostate tumors. The standard needle implantation procedure in brachytherapy uses pre-operatively acquired image data displayed as slices on a monitor beneath the operation table. Since this information allows only a rough orientation for the surgeon, the position of the needles has to be verified repeatedly during the intervention.

Within the project MEDARPA a transparent display being the core component of a medical Augmented Reality (AR) system has been developed. There, pre-operatively acquired image data is displayed together with the position of the tracked instrument allowing a navigated implantation of the brachytherapy needles. The surgeon is enabled to see the anatomical information as well as the virtual instrument in front of the operation area. Thus, the MEDARPA system serves as 'window into the patient'.

This paper deals with the results of first clinical trials of the system. Phantoms have been used for evaluating the achieved accuracy of the needle implantation. This has been done by comparing the output of the system (instrument positions relative to the phantom) with the real positions of the needles measured by means of a verification CT scan.

Keywords: Brachytherapy, augmented reality, image-guided surgery, navigation, tracking, computed tomography, image registration, registration accuracy, validation

1. INTRODUCTION

The existing cancer treatment methods have all their advantages in different areas. Brachytherapy is a method which is often used when a tumor relapse is occurring after the patient has been exposed to radiation during a previous radiation therapy with external beams. In this case it is prohibited to irradiate this relapse with such

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beams once more since the dose rate for the surrounding tissue, which is always affected through percutaneous radiation therapy, cannot be increased without provoking a severe risk.

Brachytherapy as an interventional method applies the required dose rate only to the target region by irradiating the tumor from the inside. In high-dose radiation therapy (HDR) this is achieved by inserting radioactive sources into hollow needles, which have been implemented in a preceding step. The positioning of these canulas is commonly performed employing pre-operationally acquired 3D CT image data, which is displayed slice by slice on a monitor beneath the operation table. Thus, the procedure requires a lot of experience since the surgeon has to navigate without direct line of sight. For lowering the risk of needle misplacement, the needle positions have to be checked repeatedly representing a time-consuming and patient-stressing procedure.

Within the MEDARPA[1] project a transparent display has been developed aiming on the support of minimal invasive interventions. As the core component of a medical Augmented Reality (AR) system it allows the visualization of the anatomical information and the tracked instruments simultaneously in front of the patient. One of the application scenarios this AR system is tested with is the needle implantation in brachytherapy of the prostate.

A hybrid tracking system has been developed employing an optical and a magnetic system (see section 2.1 for details). The instrument tracking is carried out using the electromagnetic tracking system 'pciBIRD' from *Ascension*.[2] The accuracy tests reported here represent mainly the precision of the electromagnetic tracking. Work dealing with this topic focusing on technical aspects has been published.[3] The approach presented in this work is motivated by a real medical application and therefore more medicine driven taking into account the clinicians' demand for a more descriptive value of the system's accuracy.

The exactness of a conventional needle implantation depends on the surgeon's experience and is hard to illustrate. Risks like the injury of organs near to the target volume cannot be quantified. In this work a real value for the navigation accuracy depicting the precision of the measurement of the instruments' position and orientation is determined. This allows an estimation of the overall error of a needle implantation using the transparent display. The individual values contributing to the overall error, see references,[4–6] are not determined explicitly, but their influence will be discussed later in this work.

This paper presents first results of accuracy tests in a brachytherapy scenario with the aid of the developed AR system. Phantoms have been developed allowing the needle positioning by providing the surgeon with a 'force-feedback' similar to tissue. The accuracy of the implantation has been verified by comparing the needle positions displayed during the intervention with the real ones measured by a subsequent computed tomography (CT) scan of the phantom with needles inside.

2. MATERIAL AND METHODS

This section gives an overview of the developed AR system explaining its components and their collaboration. The process of the needle implantation is described in detail since it is delivering one of the inputs for the accuracy test. In addition, the used phantoms and the calculations necessary for the comparison of the measured and the real needle positions are explained.

2.1. OVERVIEW OF THE MEDARPA SYSTEM

The MEDARPA Medical Augmented Reality system consists of several components which are embedded in resp. attached to a trolley. A swivel arm mounted on top of it holds the transparent display (Fig. 1), the main component of the system. Figure 2 shows an early test setup in an operation theater.

The swivel arm allows the transparent display to be moved easily to the desired place such that the patient can be observed in a usual manner. The real view on the patient is enhanced with virtual information about his anatomical structures obtained from CT images. The positions and orientations of the patient, the instrument, the display, and the surgeon's viewpoint have to be known in order to provide the virtual overlay. The tracking tasks needed for this AR system are performed by a hybrid tracking system combining an optical and an electromagnetic component. This combination of both allows to compensate the disadvantages of one single tracking system.

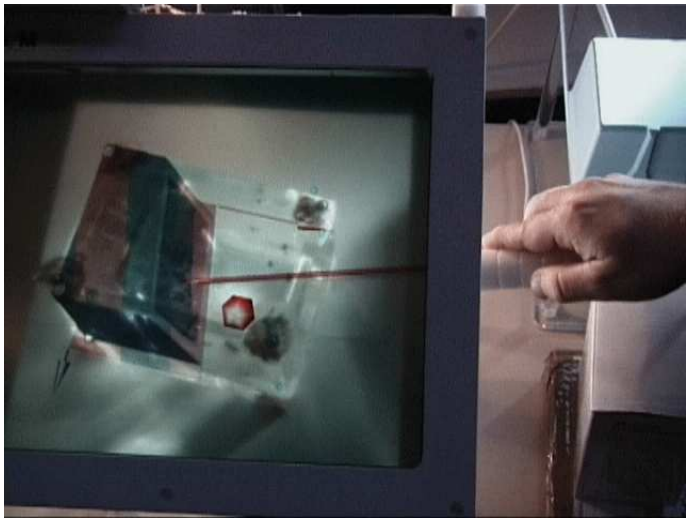

Figure 1. The transparent AR display developed for the MEDARPA system. A rendered scene based on CT data of a phantom can be seen. The phantom itself can be perceived through the display.

The non-commercial optical tracking system EOS consists of a pair of CCD cameras equipped with infrared filters. It has been developed at the ZGDV. Similar video-based tracking systems have been introduced[7–9] and few are also available on the market.[10,11] The two cameras are mounted on a stand attached to the trolley, such that the amount of occlusions is minimized, while the display and the surgeon are tracked. Tests of the optical tracking system revealed a static position accuracy of approx. $1\,mm$ within the interaction volume of the MEDARPA setup of approx. $1.5\,m \times 0.8\,m \times 1\,m$ (width, depth, height). Several six degrees-of-freedom sensors in form of rigid bodies based on infrared markers can be tracked. Active infrared landmarks are attached to the display as well as the physician's glasses. Thus, they represent the sensors allowing for the optical tracking of position and orientation.

The instrument used for the intervention is equipped with a handle that contains an electromagnetic sensor enabling a six degrees-of-freedom tracking. An electromagnetic tracking system[2] for the instrument has been chosen due to expected occlusion problems when relying on a pure optical solution.

Optical tracking systems like EOS also deliver high-accuracy tracking data and are unaffected from metallic environments, but have other problems with partial or full occlusion of the tracked objects. This is one reason, why electromagnetic tracking systems are designated to keep track of the physician's instruments. Another reason is the tendency on the market to develop electromagentic sensors with diameters of less than one millimeter, which would allow tracking inside the body by placing the sensor inside the instrument's tip. Therewith, errors induced by a large distance between the tip of a needle and a sensor located inside the handle could be avoided. However, a hybrid approach for instrument tracking, combining an optical and an electromagnetic system, is under examination for further developments.

The manufacturing of the display and its swivel arm has been planned and implemented within the MEDARPA project. It is based on a modified $17''$ TFT screen allowing a resolution of 1024×768 at 75 Hz. Due to the available display technology the transparency is restricted, but if sufficient light can be supplied to the observed scene, the display meets the transparency requirements. The current implementation of the display can easily be moved inside a working volume of at least $2m^3$ to satisfy the user's needs. All cables that are required for the input signals and the power supply are hidden inside the construction of the swivel arm.

In order to allow correct superimpositions, the pose of the patient himself and of possible instruments for the navigation have to be known. An electromagnetic tracking system[2] being part of the hybrid tracking fulfills these requirements. For the navigation itself, the accuracy of the optical tracking is of subordinate importance in the current setup. The important part for the navigation is the electromagnetic tracking, for which technical details from the specifications of the 'pciBIRD' can be found in table 1.

Figure 2. Setup of the MEDARPA system for evaluation in an operation theatre.

Degrees Of Freedom	6 (Position and Orientation)
Translation range	$\pm 76.2\,cm$ in any direction
Static Accuracy Position	$1.4\,mm$ RMS
Static Accuracy Orientation	0.5 degree RMS
Update rate	Up to 105 measurements/sec

Table 1. Details from the technical specification of the 'pciBIRD' from *Ascension*[2] with $8\,mm$ sensors.

Some further information about the MEDARPA system has been published.[12–14] See these references for more details about the system.

2.2. THE NEEDLE IMPLANTATION BY MEANS OF THE TRANSPARENT DISPLAY

As described in section 2.1, in the current state of development the surgical instrument used by the physician is tracked employing an electromagnetic tracking system. The tracking sensor is integrated in a handle which carries also the instrument, see figure 3.

The needle implantation procedure requires several steps:

- A pre-processing has to be done, by segmenting the fiducial markers and defining the target positions in the CT data set.
- The instrument for the needle implantation, equipped with an electromagnetic sensor, has to be calibrated by determining the offset between instrument tip and sensor.
- The coordinate systems of the optical and the electromagentic tracking have to be aligned.
- The patient resp. the phantom has to be registered to allow navigation and correct overlays.

The MEDARPA display does not offer a stereoscopic view on the scene. Hence, an additional navigation help compensating this lack of 3D impression is integrated: the virtual model of the navigation needle changes its

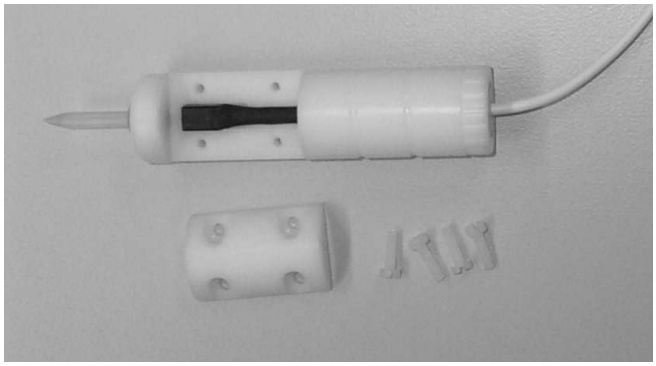

Figure 3. Instrument for registration with integrated sensor. The offset between the tip and the sensor has to be determined. A similar handle with an integrated sensor is used for embedding the brachytherapy needle.

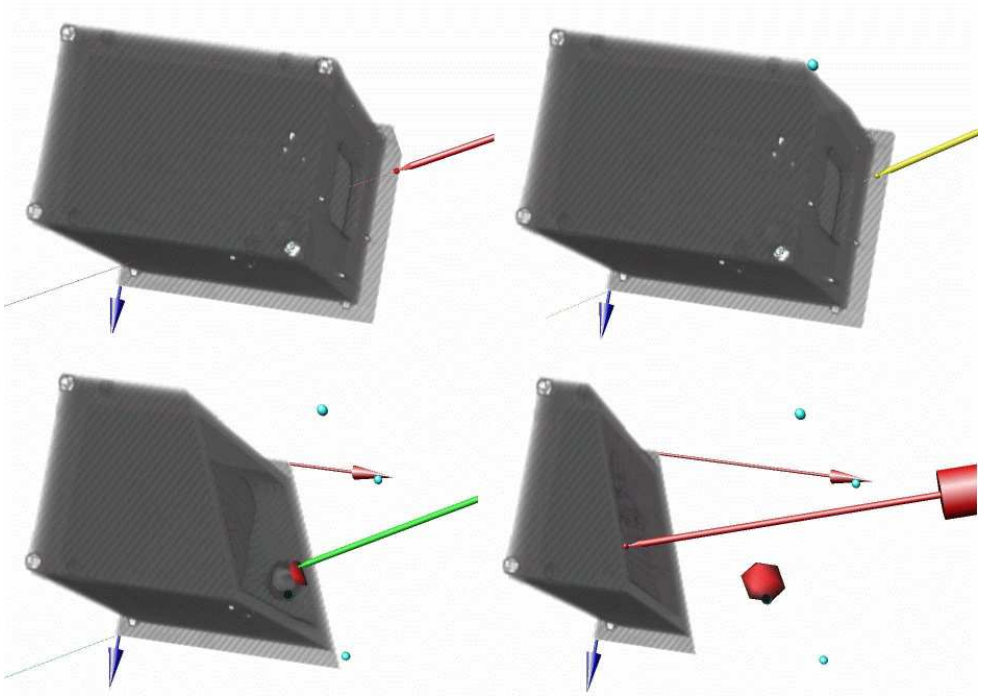

Figure 4. Four steps of navigation(left to right, up, down): searching for target direction, going along direction to target, collison with target, undetermined state.

color depending whether it is pointing in the direction of a target (yellow), or it collides with a target region (green), or it fulfills non of the cases described before (red). Figure 4 shows an examplary navigation to a target within a phantom.

The displayed needle is equipped with a virtual elongation and a clipping plane defined by the orientation of the needle which can be aligned orthogonal or perpendicular to the needle's axis. The visualization is done by a rendering module based on *OpenSG*.[15] It allows hardware accellerated rendering of a volume data set containing 256^3 voxels with up to 15 fps on current PC hardware. The frame rate is important for a real-time navigation support. In addition, a virtual model of the real instrument is visualized together with the volume data, and predefined target regions appear highlighted.

For the accuracy evaluation of the electromagnetic tracking system and the instrument calibration procedure a needle of approx. 31 *cm* in length was calibrated under laboratory conditions. This was done by keeping

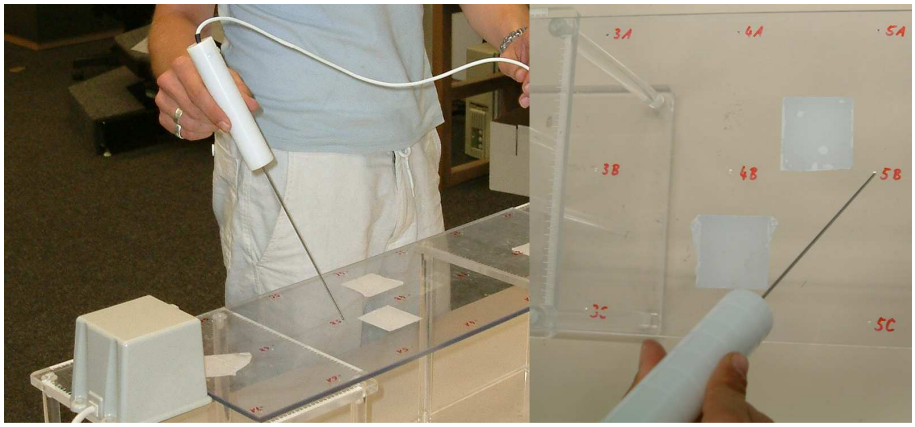

Figure 5. Measurements are recorded with instrument tip at one fixed point and sensor embedded in the instrument handle that is being moved around.

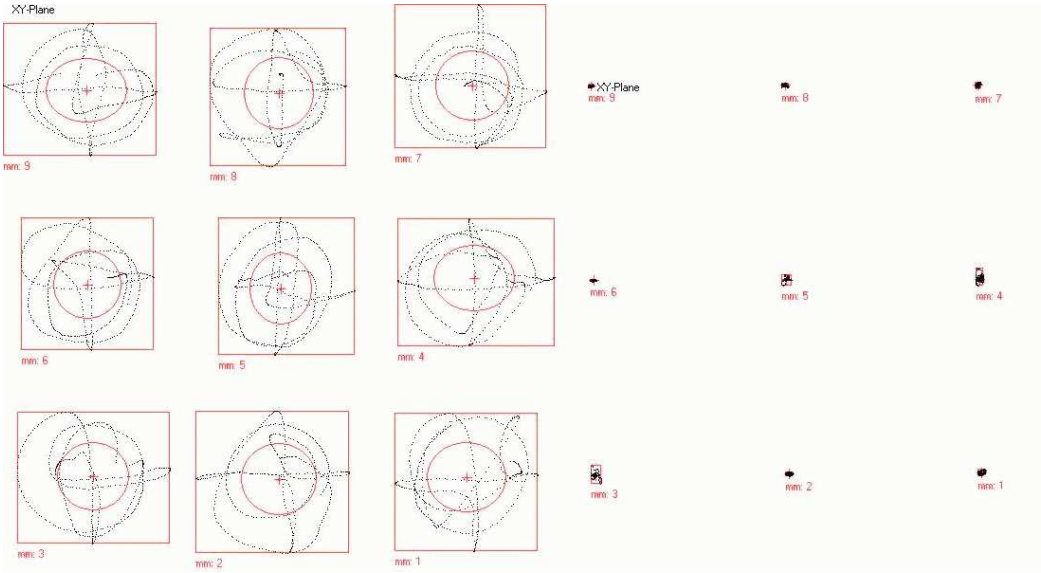

Figure 6. Recorded measurements with the instrument's tip at one fixed point and the sensor embedded in the instrument handle moved around. The positions projected onto the XY-plane are displayed. On the left side the raw measurements delivered by the electromagnetic tracking are shown, on the right side the same measurements after applying the calculated offset transformation are presented.

the tip of the needle fixed in one point at 9 positions arranged in a quadratic grid with a spacing of 100 mm, while rotating the handle until 500 measurements (rotation and translation of the sensor) were recorded for each position (see figure 5). These samples represent an overdetermined linear system reflecting the fix offset of the instrument, and the fixed position of the instrument's tip. It is solved in a least squares sense yielding the offset translation and the fixed point. That procedure is performed for each of the nine tip locations and the average offset translation of all 9 calculations are considered for the subsequent evaluation.

The result can be evaluated by applying the offset translation to all mesurements and taking the distances between the transformed measurements and the fixed point into account. It is hard to determine an absolute accuracy, since there is no absolute reference point available. A relative accuracy can be determined by comparing the measured distances between points with known physical distances. After calculating the offset from the electromagnetic sensor to the needle's tip, the evaluation of 4500 samples for each of ten tests provided the results shown in table 2.

test	offset x[mm]	offset y[mm]	offset z[mm]	offset length [mm]	offset diff [mm]	mean error at tip[mm]	mean error distances [mm]
1	312.9	−0.9	1.1	312.9	0.01	1.5	0.7
2	314.3	−0.6	1.1	314.3	1.39	1.4	0.7
3	312.6	−1.2	1.0	312.6	0.31	1.3	0.6
4	313.6	−0.3	1.2	313.6	0.69	1.6	0.9
5	312.1	−0.6	1.5	312.1	0.81	1.8	1.0
6	315.5	−0.4	1.3	315.5	2.59	2.2	1.3
7	311.3	−1.4	1.0	311.3	1.20	1.2	0.5
8	312.3	−0.7	0.9	312.3	1.61	1.4	0.4
9	311.9	−1.2	0.6	311.9	1.01	1.3	0.7
10	312.6	−1.2	0.6	312.6	0.31	1.3	0.9
mean	312.9	−0.9	1.0	312.9		1.5	0.8
stddev	1.2	0.4	0.3	1.2			
max				2.6	2.60	2.2	1.3

Table 2. Results of the calibration of the offset translation for a needle with a distance between sensor and tip of approx. 31 cm, from 4500 samples for each test. The mean offset is the average from 90 offset calculations with 500 samples each. 'Offset diff' is the difference between the offset of one test to the mean offset of all tests. 'Mean error at tip' is the average displacement of the needle's tip compared to the calculated fixed point. 'Mean error distances': Measured distances of the nine test points where the needle's tip was fixed compared to the known physical distances.

2.3. THE PHANTOMS FOR THE NEEDLE IMPLANTATION

This paper describes accuracy tests performed by means of phantoms. Several ones of them have been developed by ourselves aiming on a realistic haptic impression for the surgeon. All of them consist of an acrylic, cuboid-shaped form that has been filled with a transparent gel. For demonstration reasons an anthropomorphic hull has been developed containing such an acrylic shape (see figure 7). However, the accuracy tests described here have been carried out with cuboid-shaped phantoms without the anthropomorphic hull.

The haptic feedback of the filling is comparable to that of tissue. In addition, the gel's transparency permits a direct visual verification of the needles' position. Inside the gel a plasticine object has been installed representing the target volume, i. e. the tumor. Spherical fiducial markers visible in the CT scans have been attached to the phantoms' outer surface. They are segmented in a pre-processing step[16] and used for the image registration and the phantom registration relative to the AR system's frame of reference (see 2.1). The registration algorithms have been discussed in our previous work.[17]

2.4. REALIZATION OF THE ACCURACY CALCULATION

For the calculation of the accuracy of the needle implantation several input is required:

1. The original CT data set with determined marker positions.[16] This is the data that is displayed on the MEDARPA display during the navigation.
2. The needles' positions given by the AR system (see 2.2), in the following refered to as 'AR needles'.
3. The CT data set of the phantom with implanted needles, in the following refered to as 'real needles',

Then the calculation is done as follows (see also figure 8):

1. Input 2 is given as the coordinate (x, y, z) of the AR needle's tip and a quaternion $[(q_x, q_y, q_z), q_w]$ holding the AR needle's spatial orientation. The quaterinon is used to calculate the directional vector pointing from the tip to the end of that needle. This calculation's frame of reference is defined by the original CT data set (input 1).

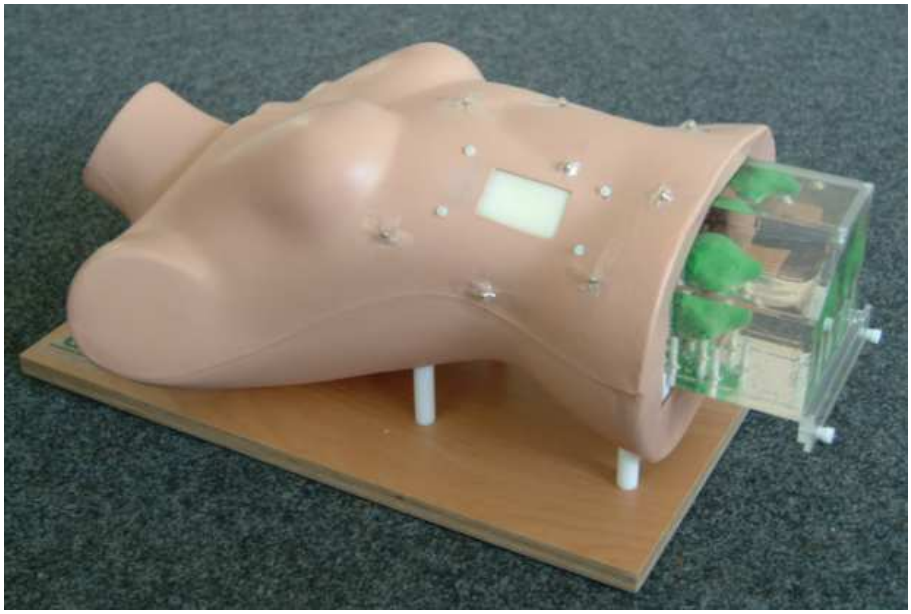

Figure 7. The anthropomorphic phantom. It contains a cuboid-shaped acrylic form similar to those used for the accuracy tests.

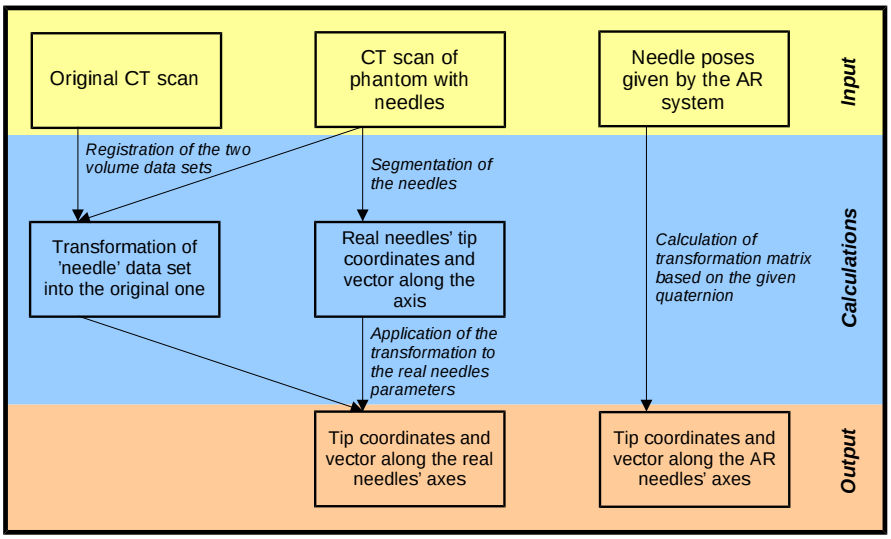

Figure 8. Data flow of the calculation process: the input data is used for the calculation of the real and AR needles' poses in the frame of reference given by the original data set.

2. The real needles' positions and directions (their 'poses') are segmented in the data set from input 3.
3. The transformation between the data set of input 3 and the original one has to be determined. Here a marker based registration method is used. The output of this step is a transformation matrix that has to be applied to all real needles' poses identified in the preceding step.
4. The positions of the 'real needle' and the 'AR needle' are compared in the frame of reference defined by the original CT data set.

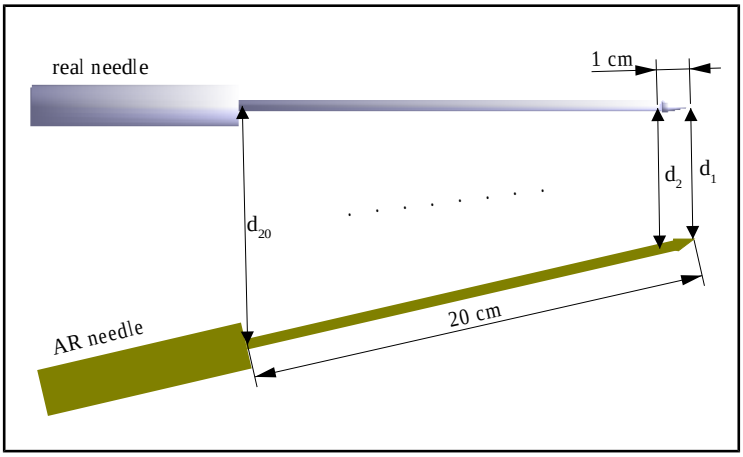

Figure 9. The distances between equally spaced positions at the axes of real and AR needle have been calculated. Samples on twenty such positions spaced at 1 cm have been taken – beginning at the needle's tip (d_1) and moving 20 cm up towards the handle.

3. RESULTS

The implantation accuracy has been verified in a first step with 8 implanted needles. In all of the cases for each needle the calculated values for the position of the tip and the orientation of the axis have been compared between the AR and the real one. In order to do that, the distances between constantly spaced positions along the axis starting at the tip and moving up in the direction of the handle have been calculated repeatedly. We compared these positions at steps of 1 cm on a length of 20 cm (see figure 9) – the typical length of a brachytherapy needle. Table 3 presents the results of the calculations. For each measurement the error at the needles' tip as well as the mean error along the needles' axes are given.

Measurement	Error at tip $[mm]$	Mean error along the needle $[mm]$
1	13.1	12.3
2	6.9	4.6
3	6.1	7.3
4	11.2	10.2
5	8.9	8.0
6	11.6	11.5
7	11.3	11.4
8	12.2	11.7
Mean of errors	10.2	9.6
Standard dev. σ	2.6	2.7

Table 3. The results of the verification of the implantation accuracy: The differences of the needle positions between the AR output and the post-implantation CT scan.

The overall accuracy of the needle implantation measured at its tip was 10.2 mm with a standard deviation of 2.6 mm. There is only a small difference between the accuracy at the needles' tips and that along the needles' axes. This indicates that the deflection of the needle is very moderate. However, the achieved results of these first measurements were not satisfying. Especially they were still too big for a real usage of the AR system in the clinical routine which is the aim of our development.

Therefore, we improved the system's setup procedure as well as the needle implantation itself in two ways. The registration error has been decreased by separating the calculation of the transformation between virtual and real patient into two steps instead of optimizing both – rotation and translation – in one step. The first

step is the determination of the translation by calculating centers of gravity and then computing the rotation separately. A detailed decription on this algorithm can be found in.[17] Furthermore, a restriction of the allowed maximum distance of the electromagnetic sensor attached to the instrument from the emitter to 50 cm prevented a navigation in areas where the accuracy of the electromagnetic tracking system is lower than specified by the manufacturer. This decrease of accuracy has been detected by further measurements similar to the early instrument calibration tests (see sec. 2.1).

A second set of test data has been acquired with a slightly shorter needle of approx. 15 cm. Together with the above improvements this lead to an increased overall accuracy of the needle implantation which was nearly twice as good as for the first measurements. A mean error of now only 6.3 mm with a standard deviation of 1.3 mm could be observed. The detailed values are given in table 4.

Measurement	Error at tip $[mm]$	Mean error along the needle $[mm]$
1	6.0	5.2
2	8.2	8.5
3	6.5	5.9
4	5.8	6.6
5	6.9	7.0
6	9.3	12.4
7	5.1	5.6
8	5.2	5.7
9	6.5	7.0
10	5.8	5.8
11	8.0	6.6
12	5.1	7.1
13	5.5	5.7
14	4.7	6.0
15	5.6	5.9
Mean of errors	6.3	6.7
Standard dev. σ	1.3	1.8

Table 4. The results of the needle implantation with the improvements concerning the registration step and the instrument navigation.

4. DISCUSSION

This work presented results of first phantom tests using an innovative AR system designed for supporting minimal-invasive interventions. The system's accuracy was measured by giving an overall error of the needle implantation. However, it would be desireable to determine the accuracy for every single step, i. e. determining the error contributed by every part of the MEDARPA system and every value generated during the examination of the acquired data. Sources of error, considering only contributions introduced by the usage of the electromagnetic tracking system, are

- the patient registration and the related pre-processing (i. e. marker segmentation),
- inhomogenities of the magnetic field created by the emitter, resp. provoked by disturbing objects like the swivel arm, the display etc. or medical devices common to a clinical environment,
- errors due to the registration of post-OP data to pre-OP data needed for transforming 'real' and 'AR needles' into the same frame of reference (see also ref.[5, 18]).

Future work will focus on this task and should also include the calculation of the target registration error as introduced by Fitzpatrick et al..[4]

The quality of the achieved accuracy can hardly be compared with results of other groups,[3] since results found in the literature mainly focus on one single part of an image-guided system giving a more technically driven value rather than a global medically driven one as we do. However, a limitation for the needle implantation accuracy is given by that of the electromagnetic tracking system. Considering the 'static accuracies' for position and orientation given by the manufacturer (see sec. 2.1) the navigation accuracy for the needle's tip is about 3 *mm* resp. 2.2 *mm* RMS. That calculation takes into account that the sensor is placed in the handle 30 *cm* resp. 20 *cm* away from the tip. Hence, the orientation error of 0.5 degree RMS contributes the main part to the overall electromagnetic tracking error. Unfortunately, that big distance between tip and sensor position cannot be decreased with the currently used system from *Ascension*.[2] Only a smaller sensor size below the diameter of the needle (like for instance the 'Aurora' system from *Northern Digital*[11]) would allow to place it inside the needle and therewith as close as possible to the needle's tip. We expect the navigation accuracy to increase significantly by doing so.

From the medical point of view the accuracy is in a range achievable by experienced doctors. Our clinical partners estimate their 'free-hand' accuracy for implementing brachytherapy needles to be around 5 *mm*. However, this does not ensure that the needle placement doesn't hurt organs-at-risk located near to the tumor. Also, the exact location of the needle has to be verified repeatedly by CT scans. The proposed AR system could help to increase the availability of the CT scanner for other tasks in the clinical routine, since only one final verification scan after the (reliable) needle impantation will be necessary. In addition, the usage of our system gives above all less experienced physicians usefull information needed for a successful placement of brachytherapy needles.

5. CONCLUSION AND OUTLOOK

The medical AR system developed within the MEDARPA project allows the support of minimal invasive interventions. First clinical tests focusing on needle implantation in brachytherapy have been carried out using phantoms. Future work will focus on the determination of the error contributed by every single part of the system. We expect to be able to increase the overall accuracy of the system aiming on a radical change of typical interstitial brachytherapy.

MEDARPA, designed as a general purpose system, will not only be used in brachytherapy. Another medical scenario we were focusing on already from the beginning of the project is to support the minimal-invasive bypass grafting by means of a telemanipulator.[19] There, our system will support the port placement by serving as a real 'magic window' that will enable the surgeon to virtually look into the patient using a pointing device. The usage of the MEDARPA system for other scenarios including minimal-invasive procedures will be evaluated in the future.

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