Published in final edited form as:

Proc SPIE Int Soc Opt Eng. 2014 March 12; 9036: 90361F-. doi:10.1117/12.2044381.

EM-Navigated Catheter Placement for Gynecologic Brachytherapy: An Accuracy Study

Alireza Mehrtash, Antonio Damato^{*}, Guillaume Pernelle, Lauren Barber, Nabgha Farhat, Akila Viswanathan, Robert Cormack^{}, and Tina Kapur**

Brigham and Womens Hospital and Harvard Medical School

Abstract

Gynecologic malignancies, including cervical, endometrial, ovarian, vaginal and vulvar cancers, cause significant mortality in women worldwide. The standard care for many primary and recurrent gynecologic cancers consists of chemoradiation followed by brachytherapy. In high dose rate (HDR) brachytherapy, intracavitary applicators and/or interstitial needles are placed directly inside the cancerous tissue so as to provide catheters to deliver high doses of radiation. Although technology for the navigation of catheters and needles is well developed for procedures such as prostate biopsy, brain biopsy, and cardiac ablation, it is notably lacking for gynecologic HDR brachytherapy. Using a benchtop study that closely mimics the clinical interstitial gynecologic brachytherapy procedure, we developed a method for evaluating the accuracy of image-guided catheter placement. Future bedside translation of this technology offers the potential benefit of maximizing tumor coverage during catheter placement while avoiding damage to the adjacent organs, for example bladder, rectum and bowel. In the study, two independent experiments were performed on a phantom model to evaluate the targeting accuracy of an electromagnetic (EM) tracking system. The procedure was carried out using a laptop computer (2.1GHz Intel Core i7 computer, 8GB RAM, Windows 7 64-bit), an EM Aurora tracking system with a 1.3mm diameter 6 DOF sensor, and 6F (2 mm) brachytherapy catheters inserted through a Syed-Neblett applicator. The 3D Slicer and PLUS open source software were used to develop the system. The mean of the targeting error was less than 2.9mm, which is comparable to the targeting errors in commercial clinical navigation systems.

Keywords

gynecologic brachytherapy; electromagnetic tracking; catheter placement; image-guided therapy; radiation therapy

1. INTRODUCTION

Cancer Facts & Figures 2013¹ states that gynecologic malignancies are estimated to be the fourth most frequent type of cancer in women in the United States and their frequency has been increasing in recent years even though the death rate has remained relatively stable at

Further author information: (Send correspondence to A.M.) A.M.: mehrtash@bwh.harvard.edu A.D.: adamato@iroc.harvard.edu.

^{*}Joint First Author

^{**}Joint Senior Author

approximately 35% of incidence. The standard care for many primary and recurrent gynecologic cancers consists of chemoradiation (concurrent chemotherapy and external-beam radiation) followed by brachytherapy.² In contrast to external-beam radiation treatment in which a linear accelerator aims radiation beams at the pelvis from outside the body, in high dose rate (HDR) brachytherapy, a source that delivers high doses of radiation travels through intracavitary applicators or interstitial catheters placed directly inside the cancerous tissue.

The purpose of this benchtop study is to measure the targeting accuracy associated with the use of a commercial EM tracking system in conjunction with computed tomography (CT) or Magnetic Resonance (MR) image guidance to place interstitial catheters in a phantom. If satisfactory levels are achieved, a bedside translation of this technology offers the future potential benefit of maximizing tumor coverage during catheter placement while avoiding insertions in organs at risk (OAR) such as bladder, rectum and bowel.

2. MATERIALS AND METHODS

2.1 Navigation Hardware

The hardware components of the system (Figure 1) consist of a navigation computer, an Aurora tracking system (Northern Digital Inc, Waterloo, ON, Canada) equipped with an EM field generator that is placed beneath the surgical table and, for catheter guidance, a navigation screen mounted in the operating room. A 1.3mm diameter, 6 DOF sensor (Northern Digital Inc) was used to detect the catheter tip position.

2.2 Navigation Software

A principle of navigation systems in medicine is the processing and display of appropriate information available in pre- or intra-operative images so as to aid in the accurate placement of instruments in the patients body and to monitor their trajectory.³ Numerous existing modules using the free and open-source software platform 3D Slicer^{4,5} as well as custom developed functionality, were used to create the user interface for navigation. The role of software in this system is to visualize the tracked catheters in the context of cross-sectional images as well as the 3D model of the segmented structures. In addition to using the 3D Slicer platform, the PlusServer application from the PLUS open source library⁶ is used to transmit the 6 DOF position and orientation of the tracked catheter to 3D Slicer using the OpenIGTLink communication protocol.⁷ The following are the four key software methods and functions employed in the navigation system.

2.2.1 Registration of MR and CT Images—MR and CT images of the phantom are co-registered in 3D Slicer. First, a set of corresponding landmarks is manually selected by the operator in each volume. A rigid transformation is then calculated by minimizing the distances between point-pairs by a least squares algorithm (Fiducial Registration Module of 3D Slicer). The results of this registration are then fine-tuned using a second method (Transforms Module in 3D Slicer) in which interactive sliders allow the operator to translate and rotate one image relative to the other while visually checking the alignment of the overlaid volumes in three orthogonal cross-sections. Visual inspection by the operator is

used to determine when the registration is adequate. For enhancing the scene visualization, a 3D CAD model of the obturator and template are also rendered.

2.2.2 Segmentation—In image-guided therapy, segmentation of the tumor and the OAR is a necessary step in radiation therapy dose planning and facilitates targeting by providing 3D dimensional visualization to the operator. A number of segmentation methods are available in 3D Slicer, including: painting brushes with thresholding and wand effects, competitive region growing, watershed methods, fast marching, and probabilistic segmentation using the Expectation-Maximization algorithm^{8,9}. Subsequent to segmentation, 3D surface models of the binary label maps can be generated using the marching cube algorithm¹⁰ that is implemented in the Model Maker module of 3D Slicer.

2.2.3 EM Coordinate System to Image Coordinate System Registration—Rigid landmark-based registration was used for aligning the EM tracker coordinate system to the CT/MR coordinate system: 1) a sequence of landmarks was selected manually on the image volume; 2) a stylus, instrumented with the electromagnetic tracking sensor, was used to touch the corresponding points on the phantom, and the software recorded the 3D positions of these points; 3) the rigid transformation for mapping the two coordinate spaces was calculated.

2.2.4 Target Selection and Visualization of Tracked Catheter—The navigation system provides real-time visualization of catheter positions and orientations with respect to the MR and CT images and surface rendered models of the applicator and targets. Using this visualization, strategies can be devised to reach the target(s).

2.3 Phantom

A commercial, synthetic gel-based phantom (CIRS, Norfolk, VA) was modified and used to evaluate the targeting accuracy of the designed navigation system. A vaginal obturator was placed in the phantom and attached to a gynecologic Syed-Neblett template, which is CT- and MR-compatible (illustrated in Figures 2-a and 2-b). Four registration catheters were placed in the phantom – their distal tips served as fiducial points for the registration of the EM tracker coordinate system to the CT/MR coordinate system. The accuracy with which landmarks can be localized in both the image and on the phantom impacts the overall targeting accuracy of the navigation system. The distal ends of brachytherapy catheters, which have a distinct appearance in CT scans and are reproducibly localizable using the EM sensor, were employed as registration landmarks in this study.

Different imaging modalities can be used in gynecologic image-guided brachytherapy. MRI of the pelvic area reveals useful structural and anatomic information whereas CT images can display the details of catheters and the applicator. Pre-procedural CT and MR images of the phantom were acquired after applicator placement but before further placement of catheters. In addition, before each insertion experiment, a CT scan was taken with the fiducial catheters in place. In order to identify fiducial points in the CT scan, copper radiopaque wires (Figure 2-c) were inserted in the fiducial catheters. The fiducial point (catheter tip) is depicted in the CT. These radiopaque wires are designed to localize the tip position

accessible to an HDR brachytherapy source inside the catheter. Figure 2-d shows two structures (labeled as A and B), which are considered organs of interest and added to the navigation scene during the procedure; they are visible in the MR image but not in the CT (Figure 2-e). In clinical cases, these structures can play the same role as tumors and OAR in navigational approaches. Figure 2-f shows the results of MR and CT registration.

The navigation scene (Figure 3) was created by aligning the MR, CT, and 3D models of template and obturator. Structure A was segmented using the threshold painter, structure B was delineated with the grow-cut segmentation tool,¹¹ and the resulting 3D models were created and added to the scene. The EM tracker coordinate system was then registered to the image, and the real-time position of the catheter with respect to the phantom was added to the scene.

3. ACCURACY EVALUATION EXPERIMENTS

Two independent sets of experiments were performed to evaluate the accuracy of image-guided catheter placement using the proposed navigation system.

3.1 Experiment 1: Using 12 Catheter Tips as Targets

In this experiment, one operator (AM) created targets by placing twelve commercially available 6F brachytherapy catheters (Nucletron Inc., Netherlands) in the phantom such that their tips covered structure A. The same operator also placed four additional catheters, two on the surface of the template and two on the distal end of the obturator, so that their distal tips would serve as fiducial points for the EM tracker to image registration. After the insertion of all 16 catheters (12 targets, 4 fiducials), a CT scan of the phantom was acquired and the target catheters were removed. This CT scan was used as a navigation map for the subsequent targeting evaluation procedures. Three different operators (NB, LB, AM) performed four navigated insertion procedures with the goal of reaching the twelve distal catheter tip targets with the help of the navigation map. The fiducial catheters remained in the same positions during the entire experiment. A total of 48 catheters were inserted with the guidance of the navigation system. The transparent phantom was covered with opaque material during the experiments so that the operators could not inadvertently gain additional visual information about the actual trajectory of their needles. Following each set of 12-catheter insertions, a confirmatory CT scan was acquired and the results were compared with the planning CT scan to calculate the targeting error.

3.2 Experiment 2: Using Three Gold Seeds as Targets

In this experiment, one operator (AD) placed gold seeds and fiducial catheters inside the phantom. He then covered it with an opaque material and provided it to the second operator (AM), who acquired a CT scan and performed the remainder of the experiment. AM located the three targets in the CT scan and planned the insertion by finding the specific template hole and depth of insertion. The navigation system was used to guide three catheters to hit the gold targets. After the insertion, a confirmatory CT scan was taken in order to calculate the distance between the gold seeds and the catheter tips so as to determine the targeting accuracy of the placement system.

4. RESULTS

4.1 Experiment 1: Using 12 Catheter Tips as Targets

The targeting accuracy was evaluated based on 48 catheter insertions from four procedures. After each procedure, a CT scan of the phantom with the placed catheters was acquired and registered to the planning CT scan. Distances between corresponding catheter tip positions were used to calculate targeting errors. Figure 4 shows the appearance of the target catheters in the planning CT scan and the 3D models of the placed catheters that are extracted using the 3D Slicer iGyne module¹² from the post-insertion CT scan. The mean and standard deviation of the targeting error from each of the four procedures is shown in Table 1.

The targeting error for each of the catheters, across the four placement procedures, is illustrated in Figure 5a. The distances for different catheter insertion in the X-Y plane (mediolateral plane (X) and anteroposterior plane (Y)) was also calculated and is depicted in Figure 5b.

4.2 Experiment 2: Using 3 Gold Seeds as Targets

In this experiment, the targeting error was computed as the Euclidean distance between the tip position of the placed catheters and the corresponding center of the gold seeds. Figure 6 illustrates the catheter tips and the gold targets in the confirmatory CT scan. Table 2 shows the mean and standard deviation of the targeting error averaged over three catheter placements by a single operator.

5. DISCUSSION AND FUTURE DIRECTIONS

We have designed and deployed a method for evaluating image-guided catheter placement accuracy with a mean targeting error of 2.89mm over 48 catheter placements by 3 different operators in a benchtop experiment that closely mimics interstitial gynecologic brachytherapy. Similarly, in a single user experiment aimed at targeting implanted fiducials in a phantom, we measured a targeting error of brachytherapy interstitial catheters <3mm. A key difference between this study and previous studies assessing targeting error is that our study used brachytherapy markers to estimate the distance between target and catheter tip. It is clinically relevant that the catheter tip measured using this methodology corresponds to the tip dwell location of an HDR brachytherapy source. A distance exists between the tip dwell location and the physical tip of the catheter to allow for clearance of the source. Therefore, in our set of experiments, a perfect position may not correspond to a targeting error of 0 mm. Exact evaluation of this effect and of possible misalignment between the location of the EM tracking probe and the tip dwell location will be performed in the future. Although it is not possible to extrapolate these results to in vivo experiments, the accuracy observed in this study is consistent with the clinical need for precisely positioning interstitial catheters in a tumor without piercing adjacent critical structures. Furthermore, given a particular selection of template insertion hole, the visualization of catheters and extrapolation of possible catheter paths may prove useful for real-time planning of the catheter configuration. The next steps will include fabrication of catheters with embedded EM sensors followed by an evaluation of targeting accuracy and placement time with and without navigation. Future validation of these results using patient data will allow for the

estimate of potential benefits of using EM technology in brachytherapy: reduction in implantation time, reduction of frequency of OAR perforation, and increased tumor coverage resulting from optimal positioning of the catheters.

ACKNOWLEDGMENTS

This work was partially supported by NIH grants P41EB015898, R01CA111288, U54EB005149, R03EB013792 and by a Kaye Family Grant.

REFERENCES

- [1]. American cancer society, cancer facts & figures 2013. 2013.
- [2]. Viswanathan AN, Thomadsen B. American brachytherapy society consensus guidelines for locally advanced carcinoma of the cervix. part i: General principles. Brachytherapy. 2012; 11(1):33–46. [PubMed: 22265436]
- [3]. Cleary K, Peters TM. Image-guided interventions: technology review and clinical applications. Annual review of biomedical engineering. 2010; 12:119–142.
- [4]. Pieper, S.; Lorensen, B.; Schroeder, W.; Kikinis, R. The NA-MIC kit: ITK, VTK, pipelines, grids and 3D Slicer as an open platform for the medical image computing community. Apr. 2006
- [5]. Fedorov, A.; Beichel, R.; Kalpathy-Cramer, J.; Finet, J.; Fillion-Robin, J-C.; Pujol, S.; Bauer, C.; Jennings, D.; Fennessy, F.; Sonka, M., et al. Magnetic Resonance Imaging. 2012. 3D Slicer as an image computing platform for the quantitative imaging network.
- [6]. Lasso, A.; Heffter, T.; Pinter, C.; Ungi, T.; Fichtinger, G. Medical Image Computing and Computer-Assisted Intervention (MICCAI 2012) - Systems and Architectures for Computer Assisted Interventions. The MIDAS Journal; Nice, France: Oct. 2012 Implementation of the plus open-source toolkit for translational research of ultrasound-guided intervention systems; p. 1-12. The MIDAS Journal 2012
- [7]. Tokuda J, Fischer GS, Papademetris X, Yaniv Z, Ibanez L, Cheng P, Liu H, Blevins J, Arata J, Golby AJ, et al. Openiglink: an open network protocol for image-guided therapy environment. The International Journal of Medical Robotics and Computer Assisted Surgery. 2009; 5(4):423–434.
- [8]. Wells WM III, Grimson WEL, Kikinis R, Jolesz FA. Adaptive segmentation of mri data. Medical Imaging, IEEE Transactions on. 1996; 15(4):429–442.
- [9]. Kapur T, Grimson WEL, Wells WM III, Kikinis R. Segmentation of brain tissue from magnetic resonance images. Medical image analysis. 1996; 1(2):109–127. [PubMed: 9873924]
- [10]. Lorensen WE, Cline HE. Marching cubes: A high resolution 3d surface construction algorithm. ACM Siggraph Computer Graphics. 1987; 21(4):163–169.
- [11]. Vezhnevets V, Konouchine V. Growcut: Interactive multi-label nd image segmentation by cellular automata. proc. of Graphicon. 2005:150–156.
- [12]. Pernelle, G.; Mehrtash, A.; Barber, L.; Damato, A.; Wang, W.; Seethamraju, RT.; Schmidt, E.; Cormack, RA.; Wells, W.; Viswanathan, A., et al. Medical Image Computing and Computer-Assisted Intervention-MICCAI 2013. Springer; 2013. Validation of catheter segmentation for mr-guided gynecologic cancer brachytherapy; p. 380-387.

Figure 1.
The hardware components of the navigation system.

Figure 2.

(a) The gynecologic brachytherapy applicator comprised of a Syed-Neblett template and a vaginal obturator (b) The phantom (transparent) with placed applicator and four fiducial catheters. (c) The visibility of the catheter tips in the CT is enhanced by placing copper markers inside them. (d) Sagittal slice through the MR scan of the phantom shows two structures (A and B) that are not visible in CT scan (e) Sagittal slice through the CT scan of the phantom shows the applicator but the structures are not visible (f) Sagittal slice of MR overlaid on CT scan after registration shows the structures as well as the applicator.

Figure 3.

A screenshot of the navigation screen from 3D Slicer during catheter insertion experiment. (a) Axial slice through the phantom MRI that shows the catheter tip, structure A, and the obturator. (b) 3D rendering of the brachytherapy applicator CAD model, the catheter (cyan), structures A and B, and target (red sphere). (c) Coronal slice through the phantom MRI during the placement procedure; when the red trajectory of the moving catheter aligns well with target, the operator assumes the catheter placement is correct. (d) Sagittal slice through the phantom MRI showing the catheter, applicator, structures A and B, and the target.

Figure 4.

The planning CT scan and 3D models of the inserted and fiducial catheters in Experiment 1. (a) Axial slice through the CT of the phantom shows the planning catheter tip as a white dot and the placed catheter tip as a black circle. (b) 3D models of the fiducial catheters and the placed catheters. (c) Sagittal slice through the phantom: alignment of fiducial catheter model (extracted from post-placement CT) with the white line (the same catheter in planning CT) ensures the registration accuracy. (d) Coronal slice through the post-placement CT of the phantom. The targeting error is visible as the displacement between the placed and the planned catheters.

Figure 5.

Targeting errors for 48 catheters placements, performed in 4 procedures. (a) The distance between each planned and placed tip. (b) Displacement error in the X-Y plane (the plane parallel to the guiding template).

Figure 6.

Catheter tips and gold seeds in the post-insertion CT for Experiment 2. (a) Axial slice through the phantom CT shows gold seeds and catheter tips clearly. (b) 3D models of placed catheters whose tips are indicated as red balls and centers of gold seeds indicated by green balls through the axial slice of phantom CT. (c) Sagittal slice through the phantom CT and a single placed catheter relative to the corresponding gold seed. (d) Coronal slice through the phantom CT showing a second catheter and corresponding gold seed.

Table 1

Targeting error in Experiment 1. Values for mean and standard deviation of the targeting errors in four procedures, each performed by a different operator and consisting of the placement of 12 catheters using navigation.

Procedure #	Targeting error (mm)
1	2.49 ± 1.45
2	3.55 ± 3.08
3	3.10 ± 1.46
4	2.41 ± 1.09
Mean (total)	2.89 ± 1.93

Table 2

Targeting error in Experiment 2. Values for mean and standard deviation averaged over 3 catheter placements with the goal of reaching the gold seed with the catheter tip. Delta X, delta Y and delta Z are right-left, anterior-posterior and superior-inferior directions in the CT scanner coordinate system.

	delta X (mm)	delta Y (mm)	delta Z (mm)	targeting error (mm)
Experiment #2	1:22 ± 0:89	1:54 ± 0:91	1:54 ± 1:67	2:95 ± 0:83