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The Feasibility of Navigation-Assisted Mapping of Bladder Tumors During Transurethral Resection

Ronald O.P. Draga, Herke Jan Noordmans, Tycho M.T.W. Lock, Joris Jaspers, Arjen van Rhijn, J.L.H. Ruud Bosch

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ABSTRACT

Introduction: Surgical navigation systems have proven to support surgeons to localize and target anatomical structures. The aim of this study is to investigate the accuracy of reproducing bladder coordinates during transurethral resection using an optical navigation system, as a first step to assess the feasibility of accurate navigation-assisted resection of bladder tumors.

Methods: The coordinates of 21 bladder locations in 7 patients were collected using a Medtronic StealthStation Surgical Navigation System with infrared optical tracking. The coordinates of bladder lesions and ureteral orifices were recorded twice, independently, after filling the bladder with an arbitrary fixed volume of 390 mL of saline.

Results: The distance, in millimeters, between the coordinates of 2 consecutive measurements of the same bladder location was calculated. Bladder lesions and ureteral orifices could be retrieved with a mean accuracy of 8.2 mm (SD = 6.2; N = 21).

Conclusion: Navigation-assisted mapping of the bladder showed to be accurate at constant bladder volumes. Further development of the technology is needed to improve navigation efficiency and to implement augmented reality techniques to facilitate the retrieval of bladder tumors during transurethral resection.

INTRODUCTION

Navigational devices have been implemented in neurosurgery, orthopedics, and ear-nose-throat surgery to improve surgical accuracy [1-3]. These navigational devices track the coordinates of the patient and surgical instruments in the operating room. Image-guided surgery matches the coordinates from medical images with coordinates from the patient and displays the tracking instruments in real time on the preoperatively acquired volume to guide the surgeon towards anatomical targets.

In the last few years, research groups have taken it a step further and are evaluating the efficacy of navigation in soft tissues while the technique was primarily used for the navigation of bony structures. In urology, soft-tissue navigation has already proven its benefits for prostatectomy and partial nephrectomy [4-7]. The concept of relocating suspicious bladder lesions during transurethral resection by optical navigation has been presented earlier [8].

Complete tumor resection is critical for the successful treatment of bladder cancer. Noticeably, the residual tumor rate detected at second-look cystoscopy after 2 to 6 weeks is particularly high and varies between 27 to 78% [9-11]. A large meta-analysis of 2,410 bladder cancer patients performed by the European Organization for Research and Treatment of Cancer (EORTC) demonstrated that the 3-month recurrence rate after transurethral resection of a bladder tumor (TURBT) ranged between 0 and 46%. These differences are not the result of the clinical features of the tumor but probably of the quality of transurethral resection performed by individual surgeons [12]. In other words, surgeons frequently overlook and leave behind tumors [13]. Bladder diagrams and, even, photo or video documentation have been advised as a preventive measure to

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CORRESPONDENCE: Ronald Oskar Draga, M.D., Department of Urology, University Medical Center, Utrecht, Utrecht, Netherlands (r.draga@umcutrecht.nl)

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Figure 1. Endoscope mounted with the tracker and reflecting spheres.

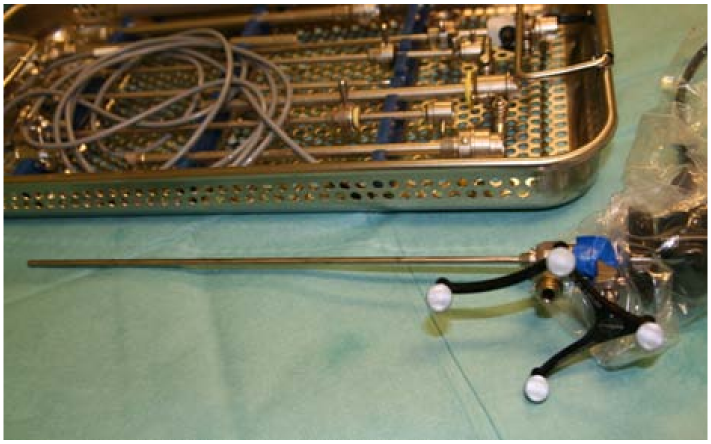
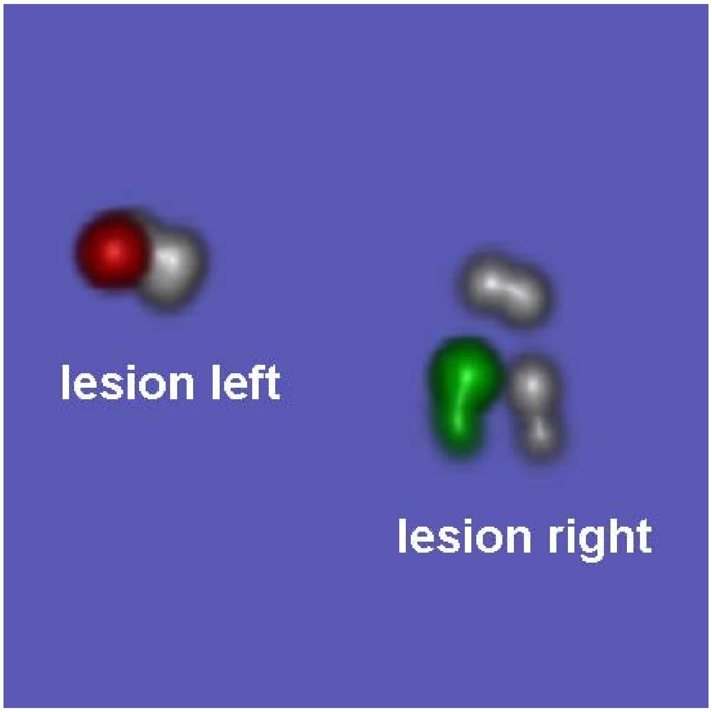


Figure 2. Virtual view of the posterior bladder wall of patient 2. Two lesions were measured with a precision of 6.9 mm and 7.1 mm, respectively.



reduce the number of residual tumors [11]. Similarly, computer-aided mapping of the bladder might contribute to accurate registration of the bladder tumor locations.

In this study, the accuracy of reproducing bladder coordinates using an optical navigation system during transurethral resection is investigated as a first step to assess the feasibility of accurate image-guidance inside the bladder. We adjusted navigation system software to track the coordinates of the tip of the probe inside the bladder [14].

Beforehand, we expected that the deformity of the bladder would impair with the reproducibility of the coordinates and that the bladder locations would readily change position when the bladder was filled and emptied again. But, if the mean error would show to be only about 1 to 1.5 centimeters, bladder lesions would be within the line of sight of the endoscope when it was held at a conventional distance of approximately 2 to 3 centimeters from the bladder wall. This would imply that bladder lesions could be found again easily and that in vivo bladder navigation is feasible.

PATIENTS AND METHODS

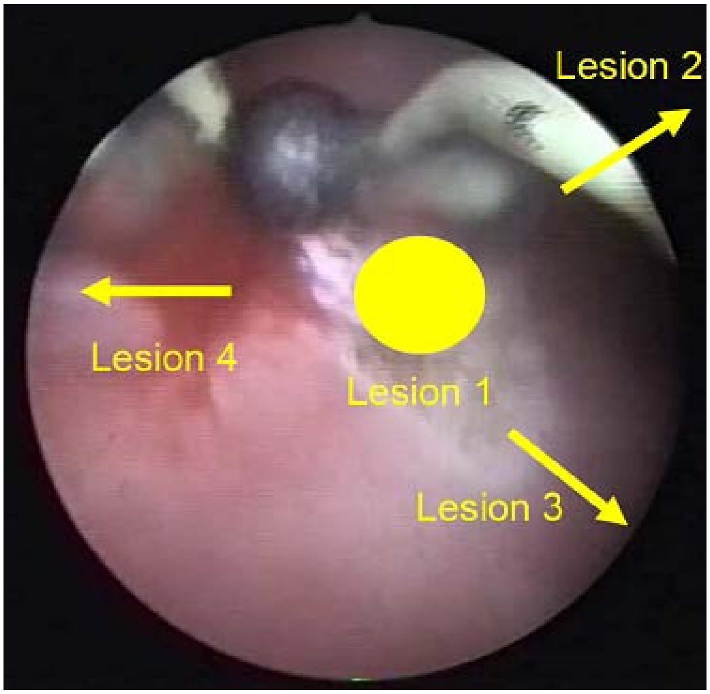
Patients

The feasibility of bladder navigation was investigated in patients suspected of primary or recurrent bladder cancer who were planned for a transurethral resection of bladder tumors. Between January and July 2008, 7 patients (4 men and 3 women) with a mean age of 65 years (range: 50 to 73 years) were randomly included in the study (Table 1). The ethics committee of our institution approved the study. Informed consent was obtained from each patient prior to the measurements.

Navigation System

A commercially available stereotactic navigation system, equipped with a stereo infrared camera for depth perception (StealthStation TREONplus, Medtronic, Inc., Minneapolis, MN, USA), was used to determine the position and orientation of the surgical instruments in the operating room. Infrared light is used to track the positions of the instruments with an accuracy of approximately 1 to 2 mm; for this, the instruments are fitted with reflecting spheres (Figure 1) [14]. Originally, the StealthStation image guidance software was designed for neurosurgery. A computed tomography (CT) scan of the patient's head marked with small plastic landmarks, called "fiducials," is imported into the navigation system. Under general anesthesia a reference arc with passive markers is fastened to the patient's head in the operating room. The positions of the fiducials and the reference arc are registered by means of a precalibrated, handheld pointing device that is also mounted with reflecting spheres. After removing the fiducials from the patient's head, the location of the tumor can be located in relation to the reference arc in order that the patient and camera can be moved during the surgical procedure. Lastly,

Figure 3. Illustration of image-guided surgery. The computer moves a virtual camera corresponding to the real endoscopic movements. Arrows and dots guide the surgeon towards lesions inside the bladder.



surgical instruments, which are fitted with passive markers, are tracked by the infrared cameras in the operating room and are visualized on the computer screen in relation to the 3-D reconstruction of the brain tumor.

We made small adjustments to the system's software so that the fiducials and preoperative CT or MRI images are not needed for initiating the navigation. The tip of the endoscope is used as a pointing device to virtually mark lesions inside the bladder and to record coordinates in "an empty virtual space."

PROCEDURE

Patients were treated under spinal or general anesthesia. The endoscope was prepared for navigation and fitted with a sterile tracker mounted with reflecting spheres. The tip of the endoscope was calibrated to enable its use as a pointer to collect coordinates inside the bladder. Before tumors were resected, the spatial coordinates of bladder locations were recorded, twice independently, after emptying and filling the bladder with a fixed volume of 390 mL (3 times 130 mL using a 150 mL syringe). Thus, between the 2 measurements the bladder was emptied and re-filled with the same volume. During the procedure the bladder was filled with irrigation fluid using a continuous flow resectoscope. The precision of bladder navigation was defined as the Euclidean distance between the spatial coordinates of 2 consecutive measurements, in millimeters, calculated by using Pythagoras's equation. The coordinates were plotted in a 3-D Cartesian coordinate system. Measurements were made by 4 different surgeons. SPSS version 15.0 was used for all statistical analyses.

RESULTS

In 7 patients, the coordinates of 21 locations, 9 ureteral orifices, and 12 bladder lesions were recorded (Table 1). The mean registrational precision for all bladder locations was 8.2 mm (95% CI 5.3 to 11.0 mm; N = 21; range: 1.0 to 25.6 mm; SD = 6.2). The bladder coordinates of each patient were rendered in virtual space (Figure 2). Ureteral orifices could be retrieved with an accuracy of 8.1 mm (95% CI 2.1 to 14.1 mm; N = 9; range: 1.0 to 25.6 mm; SD = 7.8). Bladder lesions could be found again with an accuracy of 8.2 mm (95% CI 5.0 to 11.5 mm; N = 12; range: 1.5 to 19.2 mm; SD = 5.1). None of the patients underwent a re-TURBT within 6 weeks after the procedure.

In patient 5, the precision of reproducing the coordinates of the right ureteral orifice and a tumor on the left bladder wall were 25.6 mm and 11.3 mm, respectively. Both coordinates shifted toward an infero-posterior direction. This shift was due to the patient's coughing fit, thereby moving slightly forward on the operating table and causing a change in the position of the bladder relative to the first measurements. The mean time to recurrence for patients was 13.1 months (Table 1).

DISCUSSION

In this study we demonstrated that bladder navigation is accurate in a clinical setting. Recent laboratory tests on a phantom model at our institution have shown an overall mean accuracy of 3.0 mm (SD 2.3) and successful navigation of 93.8% [15]. In the last study a newly developed target was successfully used to improve the tracking of the endoscope movements.

Other research groups have investigated computer-aided methods for previous mapping of the bladder. First, inertial navigation makes use of accelerometers and gyroscopes to track endoscope movements. Behrens et al. have shown that inertial tracking for bladder endoscopy produces an overall accuracy of < 1°, 2 °, and 4° in vertical, horizontal, and axial directions, respectively [16]. Inertial navigational devices can be produced at a low cost and have become popular in the gaming industry where it is combined with LED-induced optical navigation to continuously recalibrate the axes of the inertial system [17,18].

Second, magnetic tracking uses a magnetic field to visualize the maneuvers of flexible endoscopes on a secondary video screen. Shah et al. investigated the benefits of magnetic tracking.

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Table 1. Precision of the measurement of bladder coordinates using an optical tracking device.

Patient	Gender	Age (years)	Locations	Histopathology	Precision (mm)[a]	Recurrence (months)	Recurrence Histopathology
1	female	50	left ostium	N/A	2.99	-	-
2	male	62	posterior bladder wall/ left	inflammation	6.85	-	-
		62	posterior bladder wall/ right	inflammation	7.11		
3	female	59	posterior bladder wall/ right	pTaG1	1.45	15.6	pTaG1
		59	posterior bladder wall/ left	pTaG1	4.32		
		59	left ostium	N/A	1.02		
4	male	66	right bladder wall	pTaG1	4.84	17.7	pTaG1
		66	right bladder wall	pTaG1	5.7		
		66	left bladder wall	pTaG1	6.51		
		66	right ostium	N/A	9.42		
		66	left ostium	N/A	4.35		
5	male	72	left bladder wall	inflammation	11.34	-	-
		72	right ostium	N/A	25.6		
6	male	69	right bladder wall	pTaG1	9.52	8.7	pTaG1
		69	dome	normal	19.22		
		69	right ostium	N/A	2.74		
		69	left ostium	N/A	3.73		
7	female	73	right ostium	N/A	8.65	10.3	pTaG2
		73	left ostium	N/A	14.51		
		73	right bladder wall	pTaG2	5.55		
		73	posterior blader wall	inflammation	16.36		

[a] The coordinates of the bladder locations were determined twice. The precision was defined as the Euclidean distance between the 2 coordinates, in millimeters. N/A: not applicable.

They showed that the technique allows accurate straitening of loops during colonoscopy and reduces intubation times [19]. A disadvantage is that magnetic tracking is disturbed by the vicinity of magnetic-responsive materials, which would hamper the navigation during transurethral resection with iron instruments. Magnetic tracking could be beneficial in the outpatient clinic to map the bladder during flexible cystoscopy. When a bladder map is created in the outpatient clinic by flexible cystoscopy it could be uploaded in the operating room to start the navigation-assisted transurethral resection.

Third, virtual cystoscopy by CT and magnetic resonance imaging (MRI) was used to visualize bladder tumors in a virtual environment [20,21]. Major limitations are that the current helical CT and MRI resolutions do not allow the detection of lesions < 5 mm. Biopsies are often required to distinguish between inflammation, fibrosis, and cancer [20].

Fourth, 3-D panoramic views of the bladder mucosa can be generated by fusing together endoscopic images [22-27]. Miranda-Luna et al. were the first to describe mosaicing of the bladder in vivo. They found that clinicians appreciated the continuity of marks, spots, and blood vessels and could quickly retrieve the regions of interest [22]. In laparoscopy, panoramic views have shortened operating time and reduce blood loss [23]. The quality of bladder mosaic computation will almost certainly improve in the coming years because of increased computer-processing speeds. New computer software programs have shown to correct for surface distortions and identify bladder mucosa features with millisecond calculation times, similar to inside-out tracking that utilizes landmarks inside the patient for navigation without the need for external tracking devices [6]. Yoon et al. described the use of an automated steering mechanism to ensure that images of the entire bladder surface are produced, which may support mosaicing of the bladder [28].

Lastly, in many medical fields we have seen that the combination of 2 or more techniques will improve the efficacy of individual techniques. Optical tracking may be combined with inertial navigation and/or inside-out navigation to ensure the continuation of tracking at all times and to add to the overall navigational accuracy.

In a final stage, the navigation system will have to incorporate augmented reality to visualize the locations of bladder tumors onto the video screen (Figure 3). Augmented reality refers to the integration of images from a virtual environment with video images from the "real world." In this way, arrows and dots could guide the surgeon toward marked bladder lesions.

A limitation of soft-tissue navigation is the influence of tissue deformation and organ shift. In liver surgery, researchers found an average movement of the liver surface of 10.3 mm ± 2.5 mm [29]. In cardiovascular surgery, augmented reality was successful in determining the best access port for thoracoscopic surgery. The accuracy of localizing coronary arteries was 9.3-19.2 mm [30]. In neurosurgery, brain shifts of 10 mm caused by cerebrospinal fluid leakage and tumoral volume resection have been reported [31,32], which is within the range of our results. In contrast to the latter examples, in bladder navigation, point-to-point accuracy for retrieving tumors would not be needed because the endoscope portrays endoscopic images. Even if there is some inaccuracy, bladder lesions will appear within the line of sight of the endoscope.

Some limitations of our study and the optical navigation system should be mentioned. First, for this feasibility study, we filled the bladder twice with the same volume; however, most cystoscopy systems fill the bladder to a maximum after which the bladder is emptied manually. Surprisingly, we observed that varying bladder volumes did not change bladder coordinates considerably. This could be explained by the bladder's geometry; if the bladder is regarded as a perfect sphere and the volume increases by 10% (the volume is defined by $V = 4/3 \cdot \pi \cdot r^3$, where r is the radius), the radius increases only by 3%. On the other hand, the bladder is not a perfect sphere and is subject to tissue deformations. The bladder volume could be kept at a relatively constant volume by using a continuous flow resectoscope. In addition, computer software programs could adjust for soft tissue distortions [6,22]. We expect that smaller bladder volume variations due to urine production, bleeding, and the removal of bladder tumors would not cause significant inaccuracies. Second, the optical navigation system needs a permanent line of sight to the reflecting spheres. Since the operational volume between the legs of the patient is limited, the surgeon had to move backwards occasionally to allow the camera to detect the endoscope marker. A combination of optical tracking with inertial navigation and/or inside-out tracking would circumvent this problem [18]. Third, in patient 5, a significant navigation error was observed due to a shift of the patient's position. It might be inconvenient to fit the patient with a fixed reference point and, therefore, movement of the bladder caused by cough, bowel movements, and obturator reflex will impair the precision of the system. However, the system may be easily re-calibrated by the use of anatomic landmarks such as the urethra neck or ureter orifices. Last, no follow-up data are provided to show that this technology reduces the number of recurrences. In future research it would be worthwhile to perform a randomized controlled trial to evaluate the number of recurrences after navigation-assisted and standard TURBT, random biopsies, and region-of-interest (ROIs) photographs.

Further improvements of the optical navigation system could be suggested. Reflecting spheres or even LED lights could be attached directly to the camera at the base of the cystoscope. Since transparent plastic sheets only partially block the infrared light, these sheets may even cover the cystoscope marker, which would leave out the need of a sterile marker resulting in a simple "plug-and-perform" system. In addition, stereotactic cameras could be placed at fixed points in the operating room; for example, at the ceiling of the room, shortening the system's setup time. Optical tracking in combination with inertial navigation has improved and has become cheaper over the years [17,18]. The tracking device, a computer, and navigation software could be provided for as low as $15,000 (USD).

Image-guided navigation could be useful for several reasons. First, bladder navigation could help the surgeon ensure that the bladder is fully inspected. Video feedback shows bladder lesions that have been registered before and portrays areas that need further inspection. This might decrease the number of tumors left behind inside the bladder after transurethral resection. It might also be valuable for the surgeon in legal disputes when patients present with early tumor recurrences, to confirm that tumors were not visible during an earlier transurethral resection procedure. Second, conventional documentation is suboptimal and does not show the exact location of bladder lesions. Bladder navigation could help to retrieve bladder locations accurately, especially in critical situations such as cases of multiple tumors and bleeding. Last, an electronic map of the bladder may be useful for follow-up. An overlay of a previous bladder map could redirect the surgeon to earlier resection sites for careful inspection. The positions of the ureteral orifices may be used as landmarks to fit the previous bladder map over the bladder in subsequent resection procedures.

In conclusion, navigation-assisted mapping of the bladder has shown to be accurate at constant bladder volumes. Further development of the technology is needed to improve navigation efficiency and to implement augmented reality techniques to facilitate the retrieval of bladder tumors during transurethral resection.

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