Annals of Surgical Oncology 14(2):405–410
DOI: 10.1245/s10434-006-9103-z

Image Guidance during Abdominal Exploration for Recurrent Colorectal Cancer

Ergun Kocak, MD,[1] Osama Al-Saif, MD,[1] Martin Satter, PhD,[2] Mark Bloomston, MD,[1] Shahab F. Abdessalam, MD,[1] Joseph Mantil, MD, PhD,[2] A. Ardeshir Goshtasby, PhD,[3] and Edward W. Martin Jr., MD[1]

[1]Department of Surgery, Division of Surgical Oncology, The Ohio State University, Columbus, Ohio, USA
[2]Department of Nuclear Medicine/PET, Kettering Memorial Hospital, Dayton, Ohio, USA
[3]Department of Computer Science and Engineering, Wright State University, Dayton, Ohio, USA

Background: Real-time intraoperative image guidance has been successfully applied to malignancies of the head, neck and central nervous system. Few attempts have been made to apply this technology to gastrointestinal cancers. Our purpose was to determine if a computer-assisted navigation system could be accurately used at the time of abdominal exploration.

Methods: Fourteen patients with resectable recurrent colorectal cancer underwent computer tomography (CT) imaging of the abdomen and pelvis. The CT images were uploaded to a StealthStation (Medtronic, Inc., Minneapolis, MN), a device that tracks the motion of a handheld probe in the operating field and displays its position, in real time, on the uploaded images. Various anatomic points were utilized to match, or register, the patient to the images in the navigation system. After four or more anatomic points were registered, the accuracy of the registration process was computed by the navigation system and reported as the global error.

Results: A total of 23 different anatomic structures were used for registration. The median number of points used for registration per patient was 6.5 (range 5–9). The anatomic sites most commonly used were the anterior superior iliac spines, aortic bifurcation, sacral promontory, symphysis pubis, and iliac artery bifurcation. The median global error was 10.0 mm (range 6.7 mm–27.0 mm).

Conclusion: Computer-assisted navigation systems can be used to accurately deliver image guidance at the time of abdominal exploration. Future work will be directed at determining the value of this technology in the localization and resection of tumors.

Key Words: Image-guided surgery—Image guidance—Navigation—Colorectal cancer.

The efficacy of all cancer treatments is predicated on the magnitude of the tumor burden at initial diagnosis and through all therapeutic procedures. Therefore, early detection and accurate surgical resection remains essential for the treatment of cancer. Colorectal cancer is the second most common cause of cancer-related deaths in men and the third most common cause in women in the United States.[1] Overall, the one- and five-year survival rates are 83% and 64%, respectively.[1] The five-year survival rate is nearly 90% for colorectal cancers that are detected and treated early.

Surgery is the most common and effective form of treatment for colorectal cancer. Approximately 80% of patients with colon cancer experience complete clearance of gross disease with surgical intervention.[2,3] Despite this initial success, approximately

---

Received March 31, 2006; accepted May 31, 2006; published online November 10, 2006.

Address correspondence and reprint requests to: Edward W. Martin Jr., MD; 410 W. 10th Avenue, N911 Doan Hall, Columbus, Ohio 43210, USA; E-mail: edward.martin@osumc.edu

40% of these patients will ultimately develop recurrent cancer in the liver or abdominal cavity, due to inadequate detection and clearance of occult disease.[4] Technology aimed at improving the intraoperative localization of tumor-bearing tissues to guide surgical resection is lacking.

Traditional anatomic imaging such as magnetic resonance imaging (MRI) and computed tomography (CT) viewed as either radiographs or as orthogonal views on a computer screen provide two-dimensional (2-D) clues as to the location of lesions. However, data provided in this manner force surgeons to rely on their subjective interpretation in translating 2-D information into three-dimensional (3-D) spatial relationships (i.e., actual patient volume). The need to remove any guesswork has fueled the development of image-guided navigation systems, which allow the surgical instrument position in 3-D to be viewed throughout an operation relative to anatomical images acquired preoperatively. This technique is commonly known as image-guided surgery.[5]

Owing to the relatively static positions of the elements of the cranium and spine, navigation technology has mainly developed in the field of neurosurgery, where it is referred to as *neuronavigation*.[6] In its earliest implementation, rigid frames were applied to the head, and frame coordinates were related to a standard anatomical atlas which was used to identify a target location.[7] The location selected was then employed to calculate the angles and distances to be used with the frame in order to point the surgeon in the direction of the target. This method was revolutionized by the introduction of CT imaging in the 1970s, which replaced the nebulous global atlas and provided a precise, individualized 3-D map for each patient.

By 1980, passive arm-based systems were developed. These devices were capable of encoding the exact position of a surgical tool attached to the navigation arm and registering its coordinates in physical space to corresponding points on preoperative image data. These systems could display the location of the surgical instrument on preoperative imaging data in real time. The most recent advances in this area have resulted in the development of systems that provide navigation without using stereotactic frames or robotic arms.[8] Instead, utilizing infrared or magnetic detection systems, they track the motion of a selected surgical instrument in the patient space, and display their location, in real time, on registered images such as MR or CT scans.

The key step in performing image-guided surgery is the registration of the patient anatomy to anatomical image data acquired preoperatively. In this phase, an easily identifiable landmark is selected on the patient via a pointing device tracked by the navigation system. For brain surgery, these landmarks can be external fiducials glued to the patient's skull prior to MRI and left on for surgery. For spine procedures such as pedicle screw implantation, a location on the unique shape of a selected vertebra can be used. Then the corresponding points are selected on the preoperative images displayed on the navigation system's monitor. The key to landmark selection is finding points that remain spatially fixed in relation to each other during both the imaging and operation. This is easily accomplished in the brain and spine.

While image guidance has become commonplace for neurosurgical operations, little is known about its applicability in the abdomen. In the present study, we set out to determine if a set of anatomical landmarks could be found which would enable accurate navigation to less than 20 mm at the time of exploration in patients with advanced or recurrent colorectal cancer.

MATERIALS AND METHODS

Patients undergoing elective operation for advanced primary or recurrent colorectal carcinoma were enrolled in this pilot study. Written and informed consent was obtained from all patients. All protocols relating to this project were reviewed and approved by the institutional review boards at participating centers.

The primary objective was to find a set of anatomical landmarks that would enable image guidance in the abdomen with an accuracy of less than 20 mm. CT images were acquired to optimize soft-tissue contrast with a Siemens Biograph PET/16-slice CT machine. The CT images were then loaded into a StealthStaion image-guided navigation system (Medtronic, Inc., Minneapolis, MN) using the Digital Imaging and Communications in Medicine (DICOM) transfer protocol. This StealthStation was preset with a registration error cutoff of 20 mm. The cutoff sets an upper limit on the error generated in the registration of the patient to the image data. Registration errors greater than the cutoff do not allow navigation to be performed. This represents a modification of the standard 10 mm preset utilized for neurosurgical operations.

Once all of the images were uploaded, prior to the operation, the images were reviewed and specific anatomic landmarks were identified as potential registration points by the operating surgeon. After

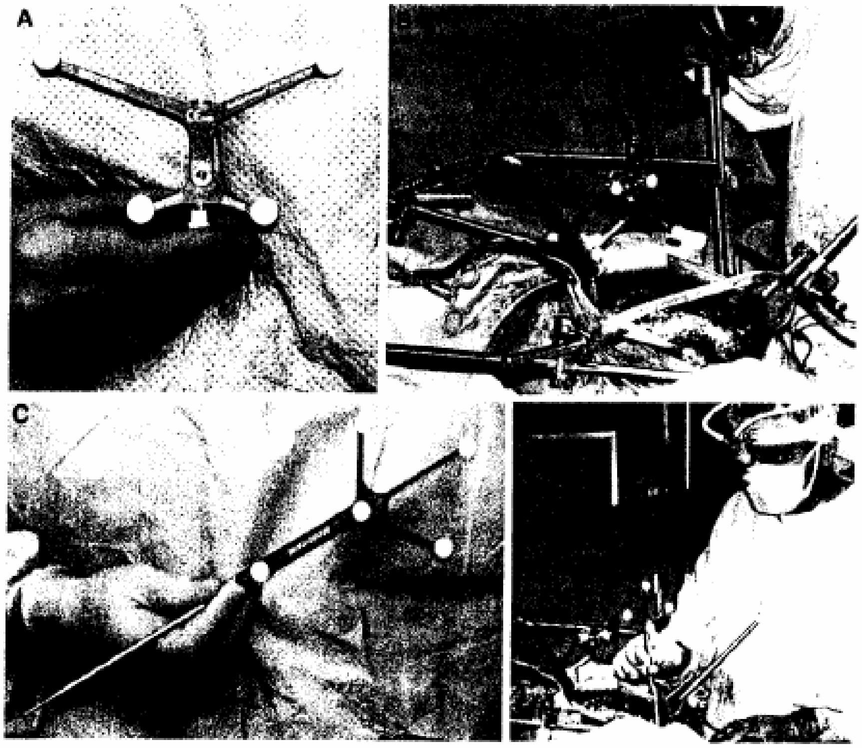

FIG. 1. Intraoperative navigation. A reference arc (A) was fixed to the abdominal self-retaining retractor (B) to provide a reference point for the navigation system. A handheld wand (C) was then used to point at structures in the operative field (D).

the abdomen was opened, the reference arc for the StealthStation was fixed to the self-retaining retractor and registration was initiated (Figs. 1A, B). The surgeon then pointed the handheld navigation wand at each of the preselected landmarks and input this point into the navigation system as a registration point (Figs. 1C, D). This process was repeated until the calculated global error was minimized. The global error is a calculated value that represents the average amount of discrepancy that occurs between the displayed position (image space) of the navigation wand and its actual position (patient space). The global error is determined after a minimum of four points have been registered and is recalculated as additional points are registered into the navigation system.

The following endpoints were recorded for analysis: the minimum global error, the names of the landmarks used as registration points, the total number of points registered to achieve a minimal global error, and the overall time to registration. Time to registration was determined as the time from registering the frame until the time that the last point utilized to obtain a satisfactory global error was registered. In each patient, additional points were registered until the global error was as close to 10 mm as possible, though an error of 20 mm was considered adequate for navigation.

RESULTS

A total of 14 patients were enrolled in this pilot study. There were five men (35.7%) and nine women (64.3%). The median age was 55 years (range 45–77 years).

At operation, four had liver metastases, six had pelvic recurrences, one had residual disease in the retroperitoneum following a previous colectomy, one had an anastomotic recurrence after low anterior resection, one had unresectable disease with peritoneal metastases that were not detected preoperatively, and one had a large tubulovillous adenoma of the upper rectum.

As described previously, the suitability of selected landmarks with respect to reproducibility and the potential navigation accuracy were measured by recording the global error, with lower values representing potentially more accurate navigation. For all cases, the median minimum global error was 10.0 mm (range 6.7–27.0 mm). As shown in Fig. 2A, the error did not improve with successive procedures. The

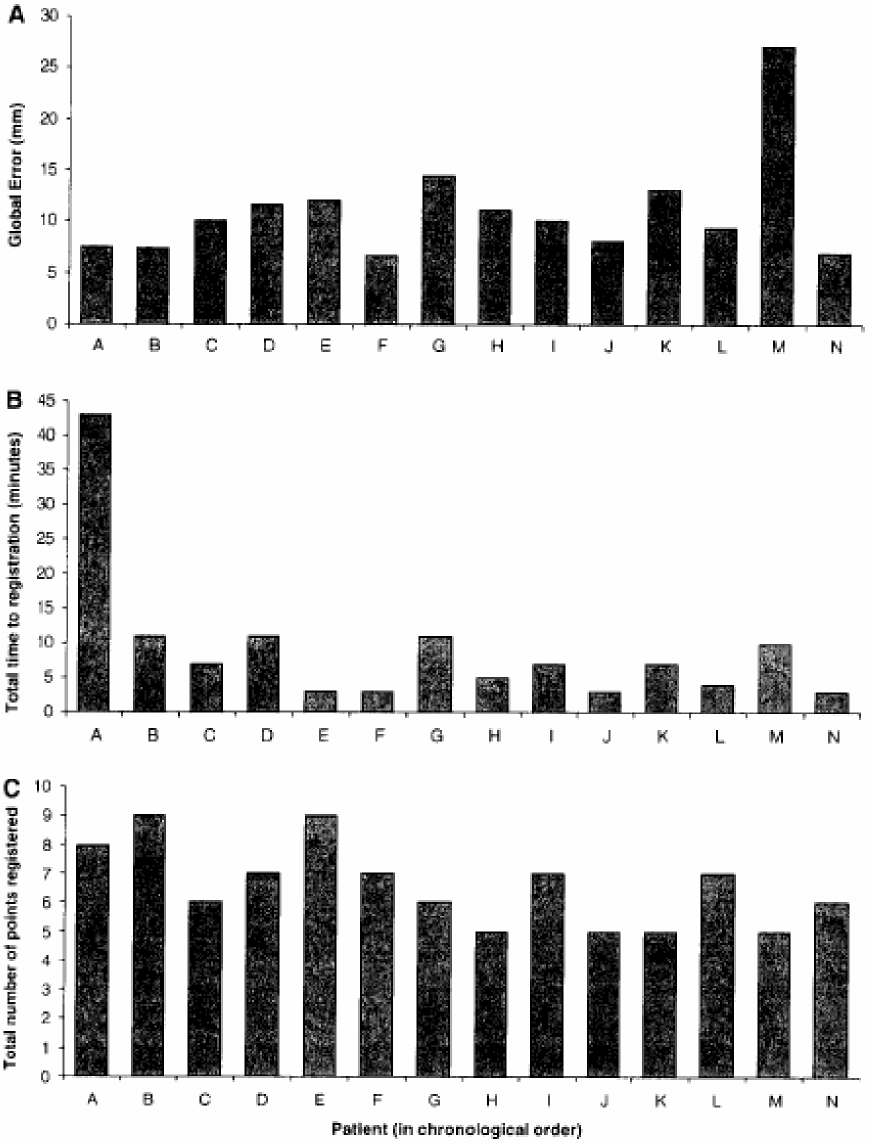

FIG. 2. Registration of anatomic landmarks was necessary to obtain a global error. (A) Global error after registration for each patient in chronological order; (B) Time necessary to obtain minimum global error for each patient; (C) Number of anatomic landmarks utilized for each patient.

minimum acceptable global error of 20 mm or less was reached in all but one patient.

The time required for registration was measured from when the handheld wand was verified, through the registration of successive anatomic landmarks, until the final registration point was entered and the minimum global error was achieved. The median time required for registration was 7.0 mins (range 3–43 mins). For the first case, the process of registration lasted 43 mins, but took 11 mins or less for the subsequent 13 cases (Fig. 2B).

A median of 6.5 (range 5–9) anatomic landmarks was required to achieve minimal global error (Fig. 2C). The seven most commonly used registration points were the right anterior superior iliac spine, left anterior iliac spine, aortic bifurcation, sacral promontory, symphysis pubis, left iliac bifurcation, and the tip of the xyphoid process (Fig. 3). While these points were used most often, no single registration point was used in all 14 patients. Conversely, a number of anatomic landmarks were used infrequently during the registration process. As demonstrated in Fig. 3, of 23 total registration points, 16 (70%) were used for registration in four cases or less. Furthermore, nine points (39%) were used for registration in only one case.

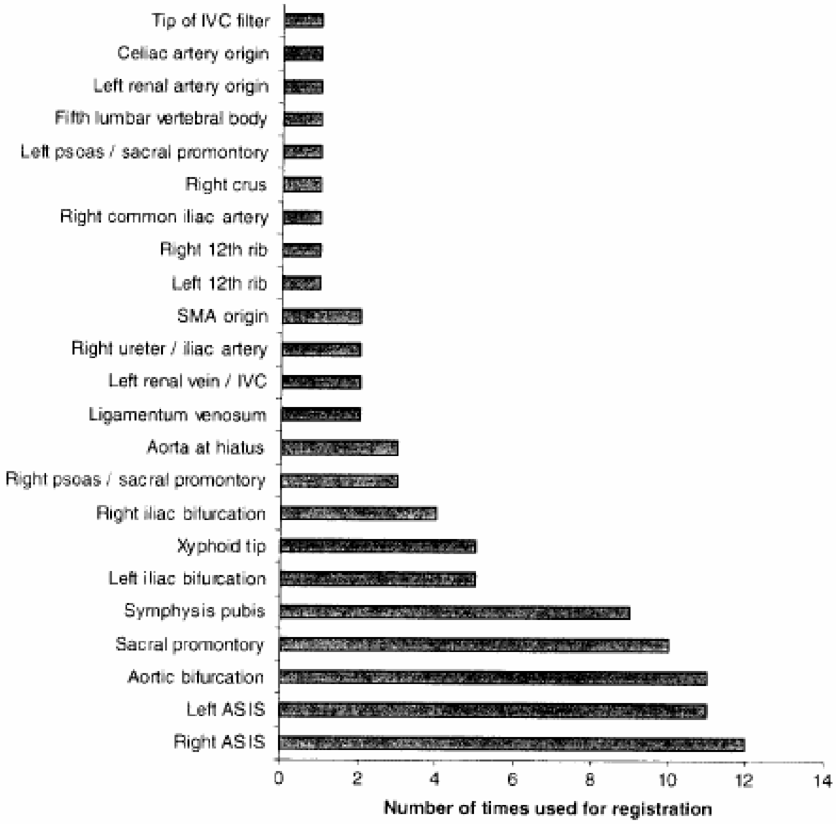

FIG. 3. The anatomic landmarks used for the registration process in all patients and the number of times each was used. SMA = superior mesenteric artery, IVC = inferior vena cava, ASIS = anterior superior iliac spine.

DISCUSSION

As the sensitivity of imaging modalities used to detect and localize tumor increases, so does the demand for effective methods to utilize this information during surgical procedures. Owing to the relatively static nature of spinal and cranial anatomy, image-guided surgery is routinely used in these areas. However, the role of such technologies during operative interventions in other regions of the body where the anatomy is more variable and subject to motion is not well characterized. In this study, we have shown that a navigation system can be successfully calibrated and applied in patients undergoing abdominal exploration for colorectal cancer using a set of anatomical landmarks to provide a global registration error of 10 mm. Furthermore, setting up and registering the navigation system was efficient, taking less than 10 minutes in most cases.

The use of computer-assisted navigation in the abdominal cavity has been previously reported. Strassman and colleagues reported the development of an electromagnetic 3-D digitizer measuring system that could be applied to provide real-time image guidance in pelvic operations.[9] This system was used to guide the accurate placement of a radiation delivery device into the pelvis at the time of resection for colorectal cancer.[10] The major limitation of the system developed by this group was that the process of registration required the use of an externally fixed fiducial. In other words, at the time of preoperative CT scanning, local anesthesia was used to fix a foreign object to the patient using a screw driven transcutaneously into the pelvic bone. Such an intervention theoretically increases the possibility of complications such as infection and introduces the discomfort with an added procedure. In our study, registration was carried out without the use of an artificial external landmark. Instead, relatively static points within the abdomen were used for the registration process. The most commonly used landmarks, such as the symphysis pubis, anterior superior iliac spines, sacral promontory, and the tip of the xyphoid process, provided relatively distinct points that were easily identified. Larger anatomic structures oriented along the long axis of the body such as the psoas muscles, iliac arteries, and the inferior vena cava do not lend themselves on CT images to the selection of a specific point. Therefore, we chose points along these structures where they intersected with other landmarks, such as the psoas muscle at the level of the sacral promontory or the inferior vena cava at the level of the left renal vein. In doing so, we were able to increase the number of locations that could be utilized as registration points. In fact, any fixed structure oriented in an axial plane can potentially be utilized as a registration point.

The accuracy of image guidance was determined by the global error. As described above, the global error is a value that is calculated by the navigation software based on registration points. It represents the average amount of error, in millimeters, that exists between the landmarks selected in the patient and image space. In most cases, we were able to visually confirm that the displayed location of the navigation probe was near the actual intraabdominal area where the probe was being pointed. However, no objective data to this effect was evaluated.

To our knowledge, this work represents the first application of an image-guided navigation system in the abdomen that is able to utilize standard preoperative CT scans (i.e., without the use of external fiducials). Future work will determine how the global error translates throughout the surgical volume by obtaining measurements of the actual discrepancy that exists during navigation, after the process of registration has been completed. Given the mobility of most abdominal organs and the natural deformation that accompanies retraction and exposure techniques, inaccuracies during navigation are inevitable as targets shift. These shifts may be accounted for through the use of intraoperative imaging and advanced registration software.[11] Finally, by combining this navigation system with preoperative positron emission tomography (PET) scanning and intraoperative imaging, the extent of resection can be tailored to the anatomy and physiology of each tumor.

ACKNOWLEDGMENTS

This work was supported by grant NIH 1 R21 EB002832-01 from the National Cancer Institute.

REFERENCES

1. *Cancer Facts and Figures: 2002.* New York: American Cancer Society, 2002.
2. Galandiuk S, Wieand HS, Moertel CG, Cha SS, Fitzgibbons RJ Jr, Pemberton JH, Wolff BG. Patterns of recurrence after curative resection of carcinoma of the colon and rectum. *Surg Gynecol Obstet* 1992; 174(1):27–32.
3. Michelassi F, Vannucci L, Ayala JJ, Chappel R, Goldberg R, Block GE. Local recurrence after curative resection of colorectal adenocarcinoma. *Surgery* 1990; 108(4):787–792.
4. Olson RM, Perencevich NP, Malcolm AW, Chaffey JT, Wilson RE. Patterns of recurrence following curative resection of adenocarcinoma of the colon and rectum. *Cancer* 1980; 45(12):2969–2974.
5. Gleason PL, Kikinis R, Altobelli D, Wells W, Alexander E III, Black PM, Jolesz F. Video registration virtual reality for nonlinkage stereotactic surgery. *Stereotact Funct Neurosurg* 1994; 63:139–143.
6. Watanabe E, Watanabe T, Manaka S. Three-dimensional digitizer (neuronavigator): new equipment for computed tomography-guided stereotaxic surgery. *Surg Neurol* 1987; 27:543–547.
7. Alexander E, Maciunas RJ. Advanced Neurosurgical Navigation New York: Thieme; 1999.
8. Golfinos JG, Fitzpatrick BC, Smith LR, Spetzler RF. Clinical use of a frameless stereotactic arm: results of 325 cases. *J Neurosurg* 1995; 83:197–205.
9. Strassmann G, Walter S, Kolotas C, Heyd R, Baltas D, Auser DD, et al. Reconstruction and navigation for intraoperative brachytherapy using the flab technique for colorectal tumor bed irradiation. *Int J Radiation Ocology Biol Phys* 2000; 47(5):1323–1329.
10. Tonus C, Debertshauser D, Strassmann G, Kolotas C, Walter S, Zamboglou N, et al. CT-Based navigation systems for intraoperative radiotherapy using the afterloading-flab technique. *Dig Surg* 2001; 18:470–474.
11. Zagorchev L, Goshtasby AA. A comparative study of transformation functions for nonrigid image registration. *IEEE transactions on image processing* 2006; 15(3):529–538.