Background: Liver surgery can be difficult because there are few external landmarks defining hepatic anatomy and because the liver has significant vascularity. Although preoperative tomographic imaging (computed tomography or magnetic resonance imaging) provides essential anatomical information for operative planning, at present it cannot be used actively for precise localization during surgery. Interactive image-guided surgery involves the simultaneous real-time display of intraoperative instrument location on preoperative images (computed or positron-emission tomography or magnetic resonance imaging). Interactive image-guided surgery has been described for tumor localization in the brain (frameless stereotactic surgery) and allows for interactive use of preoperative images during resections or biopsies.

Hypothesis: The application of interactive image-guided surgery (IIGS) is feasible for hepatic procedures from a biomedical engineering standpoint.

Methods: We developed an interactive image-guided surgery system for liver surgery and tested a porcine liver model for tracking liver motion during insufflation; liver motion during respiration in open procedures in patients undergoing hepatic resection; and tracking accuracy of general surgical instruments, including a laparoscope and an ultrasound probe.

Results: Liver motion due to insufflation can be quantified; average motion was 2.5 ± 1.4 mm. Average total liver motion secondary to respiration in patients was 10.8 ± 2.5 mm. Instruments of varying lengths, including a laparoscope, can be tracked to accuracies ranging from 1.4 to 2.1 mm within a 27-m³ (3 × 3 × 3-m) space.

Conclusion: Interactive image-guided surgery appears to be feasible for open and laparoscopic hepatic procedures and may enhance future operative localization.

Arch Surg. 1999;134:644-650

The anatomical location of hepatic tumors is usually determined preoperatively using tomographic imaging (computed tomography [CT] or magnetic resonance imaging [MRI]). This allows critical assessment of tumor resectability and assists in operative planning. However, this preoperative information at present cannot be actively used during surgery to guide resections and probe placements for ablative therapies (eg, cryoablation or radiofrequency ablation). Intraoperative ultrasonography (IOUS) can provide intraoperative imaging information regarding tumor location and surrounding vascular anatomy,1 but it requires special expertise to perform and to interpret properly. In addition, there are the following inherent technical limitations regarding its use for operative guidance in hepatic procedures: it is 2-dimensional in its present format; there can be significant interuser variation in results; and image obliteration occurs after resection or ablative therapy is initiated.

One suggested method to provide tomographic information for surgical guidance involves operating room placement of scanners.2,3 However, these systems have substantial barriers to broad acceptance. First, these units are expensive, based on installation cost, cost per procedure, and intraoperative modification of instruments to avoid magnetic interference. Second, these systems are large and can make standard operations more difficult because of space occupied by imaging equipment. Third, there is an image lag-time delay (up to 8 seconds), and, compared with MRI units placed in radiology suites.
MATERIALS AND METHODS

EXPERIMENTS TO DEFINE LIVER MOTION

Porcine Model

A porcine model was developed to quantify liver motion due to pneumoperitoneum. Pigs weighing 23 kg underwent initial laparotomy and had 8 to 10 radiopaque markers placed throughout the liver. The markers were placed on the surface as well as intraparenchymally. Surface markers were hollow plastic cylinders (inner diameter, 7 mm; height, 5 mm) filled with an aqueous solution of combined 165 mg/ml of iohexol (Conray; Mallinkrodt Medical, Inc, St Louis, Mo) and 0.5-mmol/L magnetic resonance contrast agent (Magnevist; Berlex Laboratories, Wayne, NJ), and parenchymal markers were conical cylinders filled with iohexol CT contrast (Omnipaque; Nycomed Inc, Princeton, NJ) (inner diameter, 3 mm; height, 10 mm).

Following midline laparotomy, insertion markers were placed within the liver. Surface markers were applied using polypropylene mesh and cyanoacrylate. The animal's midline wound was closed using a single layer of running suture. The animals were awakened and returned to their holding area.

After 7 days of recovery, a 5-mm laparoscopic trocar was placed in the left lower quadrant, and the animals were transported directly to the radiology suite. Helical CT scanning with 3-mm slices was performed on a helical CT scanner (Picker PQ 5000; Picker, Cleveland, Ohio). Diaphragmatic motion was controlled using end-inspiration breath-hold technique at 20 to 25 cm H2O. Following the initial scan, the abdomen was insufflated with carbon dioxide using a standard laparoscopic insufflator to 13 cm pressure and immediately rescanned using the same technique.

Image registration was performed using a mutual information algorithm on a Sun Workstation (Sun Microsystems Inc, Palo Alto, Calif). Coordinates (x, y, z) for each marker in each scan were recorded. Marker movement between preinsufflation and postinsufflation scans was determined using the Euclidean distance formula, as follows:

\[ d = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} \]

where d is the distance in millimeters between preinsufflation and postinsufflation scans; \(x_1, y_1, z_1\), the 3-dimensional CT space position of the marker before insufflation; and \(x_2, y_2, z_2\), the 3-dimensional CT space position of the marker after insufflation.

Human Liver Motion With Respiratory Changes

During open exploration for planned hepatic resection in patients with liver tumors (n = 2), points on the liver surface were tracked to determine respiratory-associated hepatic movement. After standard chevron incision and placement of a Bookwalter retractor (Codman and Shurtleff, New Brunswick, NJ), an operative probe was placed on 3 points on the liver (falciform ligament at point of entry into the liver, lateral-most tip of left lobe, and the central portion of the gallbladder fossa). Approximately 950 localization points (x, y, z) were continuously collected using the optical camera and localization pointer with IREDs from each location. Both patients had more than 2800 localization points collected during continuous respiratory cycles with standard continuous mandatory ventilator cycling.

Continued on next page
The change in position of the tracked points with respiration is calculated relative to the resting base position of the liver.

**INSTRUMENT TRACKING**

We tested the reliability of intraoperative localization and tracking of various lengths of operative probes, an ultrasound probe, and a laparoscope. The conventional neurosurgical probe is 20 cm in length and has 24 IREDs that spiral around a handle (Figure 1). Because the diameter is small compared with its length, it is relatively insensitive to roll; in addition, a “dead spot” exists if the shaft is pointed directly at the infrared camera. In laparoscopic applications, however, many complex manipulations are performed, so it is important to have created a rigid body that is sensitive to roll and minimizes dead spots. A rigid body (Figure 3) to account for these problems was designed and constructed containing 24 IREDs. An active optical position sensor (Optotrak 3020; Northern Digital, Waterloo, Ontario) was used to track instruments.12 The process of calibrating each instrument involves the following: A 3-mm diameter spherical ball is firmly attached to the tip of the probe or endoscope and placed in a corresponding cup, allowing rotation but no translation. The assembly is rotated about the tip of the scope until the position sensor has captured approximately 1000 frames of data. Once this rigid-body space is defined, the IREDs on the rigid body are mapped into that space and define the instrument tip relative to the IREDs.

The following experiment was conducted using a 20 × 20 × 20-cm cube machined with 52 divot points whose coordinates (x, y, z) in and distances relative to the other points are precisely defined. A spherical tip (1 mm) on the instrument is placed into each of 7 points on the cube (Figure 4). The computer collects the location (x, y, and z) of the tip in a divot as determined by the optical camera. Of the 7 collected points, 3 are required to perform a point-based registration. These points are referred to as fiducials. The other 4 points are referred to as targets. All 33 possible combinations of fiducials and targets were used to calculate an average fiducial registration error (FRE) and target registration error (TRE). The FRE is the measure of accuracy in locating points used for calculating the point-based registration. The TRE is a measure of accuracy in locating points (targets) not used in the registration and a better assessment of clinical accuracy. It is a function of the number of fiducials used and the ability to determine the location of the points used for registration. Because of the registration process, FRE is almost always less than TRE, but TRE is a more exacting measure of error.11

The above process was performed with 8 instrument sizes (3.5-49 cm). Three trials of 7 collection points per trial were performed for each instrument length. The 49-cm instrument trial was performed with the “gearshift knob” attached to a telecam endoscopic camera (telecam-20210130; Karl Storz GmbH & Co, Tuttlingen, Germany) with a 0° Olympus scope (Olympus America, Melville, NY). The gearshift knob attaches to all the instruments and camera via a bayonet device (Figure 3) that allows for rigid nonpermanent attachment to an instrument or laparoscope.13,14

Registration and error calculations were performed on software written in our laboratory using Borland C. Graphs (Inprise Corp, Scotts Valley, Calif) of marker position and instrument length vs error were performed on a PC workstation using a commercially available statistical package (SPSS 8.0, SPSS Inc, Chicago, Ill). Results are presented as mean ± SD.

**PORCINE LIVER MOTION MODEL**

Two pigs with an average of 9 markers each placed on or in the liver had preinsufflation and postinsufflation scans analyzed for individual marker movement. The x position change is an anatomical left-to-right change; the y position change, an anatomical anterior-to-posterior change. The z position change is on the craniocaudal axis of the animal. Average marker movement after pneumoperitoneum in the x, y, and z dimensions was 1.8 ± 12, 4.1 ± 6.4, and 0.1 ± 0.4 mm, respectively. The axial movement (z) is extremely small relative to slice thickness (3 mm). Total average marker movement for the animals was 2.5 ± 1.4 mm.

**LIVER MOTION WITH RESPIRATORY CHANGES**

Base resting liver position was calculated as the average coordinate (x, y, and z) for all points collected from the liver. Average change in position from the base is reported as a change in x, y, z relative to a reference emitter on the operative field. Liver motion is sinusoidal, and average liver position change is calculated by interpolating the peak inspiratory and expiratory position (Figure 2). Average motion with respiration was 10.3 ± 2.5 mm.

**INSTRUMENT TRACKING**

Eight instruments ranging from 3.5 to 49 cm were calibrated, tracked, and localized. Each length’s error represents more than 1000 data points collected for calibration and 280 points collected for fiducial and target registration. Five instruments ranging in lengths from 3.5 to 22.5 cm were considered open instruments. Three instruments ranging in lengths from 26 to 49 cm were considered laparoscopic instruments.
Average TRE for all instruments ranged from 1.2 to 3.2 mm, with an overall average of 1.7 ± 0.1 mm. A comparison of FRE, TRE, and the error locating a target using the worst set of fiducials in one’s registration (TRE_{max}) is presented in Figure 5.

**COMMENT**

Surgical guidance during hepatic resection or ablative procedures is currently performed with previous review of tomographic scans, tactile sensation, and IOUS. Due to intrahepatic location of large vascular structures, variability of the internal anatomy of the liver, and paucity of external anatomical landmarks, preoperative imaging not only is valuable for diagnostic purposes, but is essential for operative planning and guidance. Ablative procedures, eg, cryoablation and radiofrequency ablation, are especially dependent on precise probe placement and tissue destruction from the tumor’s volumetric center to reduce local failure. This is particularly important, since tissue margins cannot be assessed pathologically after ablation, as is done following standard hepatic resection. The IOUS can provide this guidance, but is affected by its 2-dimensional nature, by the sonographer’s skill, and by image ablation once resections or tumor ablations are initiated.

Laparoscopy combined with laparoscopic IOUS has been used as another method to optimize patient selection for liver resection. Although laparoscopy has the potential to decrease procedure-associated morbidity, it reduces the surgeon’s ability to palpate and visualize the liver and therefore to localize tumors. Interactive image-guided surgery has the potential to combine these separate modalities (preoperative tomographic imaging, IOUS, and laparoscopy) and to provide an active imaging process using preoperative and intraoperative information.
The combination of intraoperative and preoperative information may significantly improve laparoscopic guidance and/or allow liver procedures to be performed laparoscopically. Toward this end, we have accomplished registration of a mobile organ and developed tracked instruments for use in open or laparoscopic procedures.

Image-guided techniques have been developed and applied for neurosurgical operative procedures for several years, and our group has had significant involvement in this area. However, there are several technical limitations to the application of IIGS for hepatic surgery that have prevented an immediate use in this new area. First, unlike the skull, the abdominal wall is not rigid but moves with respiration, and markers are not easily attached to the liver preoperatively, as can be done for the skull. In addition, the liver is normally mobilized away from the diaphragm and abdominal wall in most hepatic procedures, further altering the relationship between the abdominal wall and the liver. To overcome these limitations, we are using a combination of surface and point-based registration techniques to remove the constraints of point-to-point registration and eliminate the need for extrinsic marker placement. Intrinsic points on the liver (eg, edge of falciform ligament, portal vein bifurcation) can be used as intrinsic fiducial markers for registration. In the current project, markers were placed on and in the porcine liver to measure how well the preinsufflation and postinsufflation CT scans are mapped, but were not used in the registration process. Average liver marker movement is presumed to represent overall liver movement. Our average marker movement before and during laparoscopic insufflation was 2.5 mm, using an end-inspiration breath-hold technique, and occurred in an anterior-to-posterior direction.

Tracking of liver motion due to respiratory changes has been of interest in the field of radiology, particularly for interventional procedures. To our knowledge, no other work has physically tracked an intra-abdominal organ’s motion during the respiratory cycle (Figure 2). These data are useful in our project as a means of testing system reliability. It will also be useful to model motion of the liver as we develop constraints for the IIGS system.

The instruments developed and used in our study all can be localized and tracked with a high degree of accuracy. The TREmax is a measure of the worst combination of fiducials used for the registration process. With any surgical navigation system, it is important to know expected accuracies as well as worst-case scenarios. No association between instrument length and error was demonstrated in these experiments. This is valuable as one evaluates the use of IIGS in laparoscopy. The 49-cm instrument (actual laparoscope) demonstrated an average TRE of 1.2 mm. Some additional error in our study is likely present due to the rigid, nonpermanent attachment of the gearshift knob to the camera in the laparoscopic tracking. Error related to a loose fit could be eliminated with a camera that has IREDs directly attached. We emphasize the importance of defining one’s measure of error in evaluating image-guidance systems.

Our experiments are preliminary work in the feasibility of IIGS in the field of general surgery and specifically for hepatic applications. The results answer basic engineering questions with regard to the feasibility of image-guided liver surgery.

We believe that this technology has applicability in the field of hepatic surgery and may improve definition of normal anatomy and pathologic changes. With the increasing use of ablative procedures and laparoscopy, intraoperative imaging will hold increasing significance for the general surgeon. Being able to display accurately the intrahepatic position of instruments (eg, cryoprobes, radiofrequency probes) on CT images could improve placement of probes, margins of resection or ablation, and evaluation of resectability (Figure 6). We have demonstrated that liver motion with pneumoperitoneum is small (<5 mm), and we have developed an accurate method to register the liver in a porcine model. We have demonstrated that we can track and localize a laparoscopic instrument to within 2 mm of accuracy in an operating room. This seems sufficient for hepatic IIGS, and the accuracy may improve as the equipment being used is attached directly to the localization devices. Interactive image-guided liver surgery appears to be feasible, and further investigation is warranted into the intraoperative use of image-guided systems.

This work was supported by grant BES-9703714 from the National Science Foundation, Arlington, Va, and grants NIGMS GM52798 and NRSA I F32 DK 09671-01 SB from the National Institutes of Health, Bethesda, Md.

Presented at the 106th Scientific Session of the Western Surgical Association, Indianapolis, Ind, November 17, 1998.

We acknowledge Odie Lawrence for his machining and corrections of our designs, Cindy Duncan and Tina Herron for their help with collection of computed tomographic images, and Karl-Storz GmbH & Co, Tuttlingen, Germany, for the loan of laparoscopic equipment.

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DISCUSSION

James E. Goodnight, Jr, MD, PhD, Sacramento, Calif: I will open this discussion with an anecdote which underscores the point that Dr Grosfeld made yesterday about our need to be on top of technology and the fact that we share this technology with multiple disciplines. When I received Dr Chapman's manuscript, I realized it was a technology that our neurosurgeons had recently begun to use, and so I went to them to get a perspective and information. The first person I encountered was their RN, who sets up their equipment in the OR and who makes things go smoothly. She said, “Oh, yes, I know about that. You put these infrared diodes on the scalp and that allows you to register those points on an image that is already contained in the machine.” Well, I was duly impressed. The first time I had ever heard registration used in this context was when I read Dr Chapman's manuscript. She went on to explain the technology about superimposing it on images and so forth and then stopped at one point and looked at me earnestly and said, “You know, this is really cool stuff.” And that was my reaction exactly. This is really cool stuff. Our neurosurgeons are indeed using this optotracking system. Currently it is most effective for spine work. They take their fiducial registration points, if you will, the base registration points, directly from the bony spine after they open. Neither the bony skeleton nor the spinal cord moves very much, and therefore this system provides superb localization for operation or probe placement. The system is equally effective for localizing lesions in the brain, except that the brain shifts, particularly once they turn a flap and begin to work on the brain. They use intraoperative ultrasound to test the positions (once again fiducial registration and target registration), and the software of the system utilizes the ultrasound information to update the preoperative MRI that has been incorporated into the system. This to me is a fairly dramatic process, that you can use these preoperative static images and then update them with a computer and with the probe at the time of operation. They were quite intrigued with Dr Chapman's efforts to correct for motion and apply this technique to liver surgery. They are not as fully trusting of the localization in the brain as they are in the spine. So Dr Chapman's work on motion is right on. In addition, they thought the low FRE (fiducial registration error and target registration error) which Dr Chapman is reporting to be very good tolerances.

I also discussed this paper with my colleague, Dr Phil Schneider, who is using radiofrequency probes to ablate liver lesions. He echoes the sentiments that Dr Chapman expresses in the manuscript, that ultrasound can be tricky for precise localization of these probes, particularly if one is looking inferiorly at the liver up toward the dome.

As all of us know, a surgeon sees with more than his or her eyes. Tactile stimuli are a critical part of the composite image our brains form of the operative field. Both tactile stimuli and depth are lost with current laparoscopic techniques. Dr Chapman and his colleagues offer us a highly innovative means by which we may be able to see in a composite fashion to do liver surgery, either by laparoscopic techniques or in fact to extend our range with open procedures. It is a beginning to be sure, as Dr Chapman points out, and much remains to be done to bring it to prime time. But I am certainly indebted to him and his colleagues for bringing this technique to our attention and the possible clinical use.

I have 4 questions. The first is a relatively obvious question, but I will ask it for clarification. Am I correct that our ability with this technique to determine the margins of a tumor or an interface with blood vessels in the liver is dependent on the quality of the CT or MRI images, or, for that matter, the resolution of the intraoperative ultrasound? Second, I think perhaps a very important question of this study is, as I move the liver at operation, can I still accurately localize the probe or, for that matter, the position of the tumor despite bleeding or tissue resection or the movement that I have created?

Then, particularly as I watched the video, what is the learning curve or user variation of this technique, perhaps compared to IOUS? And of course this is obviously a system under development. Could you give us some idea of the likely commercial cost—$25 000, $50 000, $300 000?

Steven C. Stain, MD, Los Angeles, Calif: I think the importance of this work is that it will allow us to utilize images, CT or MRI, in the operating room more precisely. I have 2 questions. How important do you believe it is to be able to place an instrument or a probe within 3 mm of its intended location? Most of the work that we do operatively does not allow us to place sutures or a cryoprobe within that amount of precision. Second, with the current ablative procedures, which require a half centimeter or a centimeter of margin, is a 3-mm accuracy in placement really important?

Jeffrey H. Peters, MD, St Paul, Minn: This is an exciting technology. I have 1 question. Have you thought to explore the possibility of changing your anesthetic technique with this device?
vice to either using a high-frequency or an oscillation technique, which would then decrease the liver motion?

Dr Chapman: One of the major reasons this project has been successful is that we have had one of our surgical residents, who has training and experience as a biomedical engineer, working on this project. Dr Allen Herline, who is here for this meeting.

Dr Herline has been able to help us learn the biomedical techniques and engineering background that we have to make this project successful. He has been a key part of making this project develop to the point where we are, although we do have a ways yet to go to demonstrate clinical utility.

Dr Goodnight, in response to your specific questions, the issue of imaging resolution and tumor margins in resections or ablative procedures, you are right on the mark. This technique can only be as good as the imaging which is acquired and utilized in the process, so this is only able to show you information that you gained from your prior imaging studies.

As far as the issue of mobilization of the liver during hepatic procedures, that is an issue, and this is something we are having to work with to determine what our most optimal registration methods will be. In the interest of time and because we are not as far along in this area, I didn’t get into the other methods for registration, but another technique involves surface registration where we can actually use our IRED probes to outline the surface of the liver, generate a surface rendering that can then be matched to CT-generated surface renderings, and allow for matching of the location and position of preoperative images with our operative localization procedure. This will allow us to work around the mobilization issues.

Will there be user variation? We hope that this will be minimized once this technique is fully developed. When a registration is performed, you are able to immediately get a targeting accuracy so that you can generate a fiducial error in your registration immediately, and you know what your accuracy is. There will be a threshold cutoff that we would all use, and whether that is 2 mm or 3 mm or 5 mm of accuracy in your registration, I think that will be variable. But if the registration is not a good fit, you exclude that information and start again until you do have accurate targeting. I do think there will be a learning curve with this technology. How difficult that will be remains to be seen.

You asked about cost. It’s hard to know that for certain. Right now the major costs involve the infrared camera. That camera costs between $25,000 and $50,000 in its early-development phase. The PC is a standard PC system like any of us would use in our offices that costs around $3000. The probes can be manufactured relatively inexpensively. So I would estimate the system costs to be between $33,000 and $50,000 at the present time. These costs may come down in the future. This is much more cost-efficient than an alternative concept, which involves putting imagers, for example, MR scanners, actually in the operating room.

Dr Stain asked about accuracy placement, and do we really need 3-mm accuracy? We don’t think we do need 3-mm accuracy. In the neurosurgical applications, the accuracy has been generally within 0.5 mm to 1.0 mm for the actual targeting and tumor biopsies. We have room for some error. The smallest accuracy we could achieve would be most ideal.

The other point I would mention is that in certain areas like tumor ablations, the more you are away from the volumetric center at the time an ablation is begun, the bigger your ultimate error once that tumor volume is encompassed. It is helpful to be as accurate as possible.

The issues regarding the variations in anesthetic management will require some investigation and whether or not imaging and procedure manipulations will be done at a set time in the ventilatory cycle, for example, at end-inspiration, or whether we alter ventilatory techniques to use high-flow ventilation, are issues we will have to look into and address. But certainly we believe the technique allows us to measure movement and our errors so that we will be able to control for hepatic movement during the procedures.

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Education and Peer Discussion Group Interventions and Adjustment to Breast Cancer

Vicki S. Helgeson, PhD; Sheldon Cohen, PhD; Richard Schulz, PhD; Joyce Yasko, PhD, FAAN

Background: We report a clinical trial comparing the effectiveness of education-based and peer discussion–based group interventions on adjustment to breast cancer.

Methods: Women with stage I, II, or III breast cancer (n = 312) were randomly assigned to 1 of 4 group conditions: control, education, peer discussion, or education plus peer discussion (combination). Seven groups (each comprising 8-12 women) were conducted in each of the 4 conditions (28 groups total). Adjustment was measured before the intervention, immediately after the intervention, and 6 months after the intervention.

Results: Consistently positive effects on adjustment were seen in the education groups both immediately following and 6 months after the intervention. There were no benefits of participation in peer discussion groups, and some indications of adverse effects on adjustment at both follow-up examinations. The effects could be explained by changes in self-esteem, body image, and intrusive thoughts about the illness.

Conclusions: Education-based group interventions facilitated the initial adjustment of women diagnosed with early stage breast cancer. There was no evidence of benefits from peer discussion group interventions. (1999;56:340-347)

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