Technology Improvements for Image-Guided and Minimally Invasive Spine Procedures

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***Abstract*—This paper reports on technology developments aimed at improving the state of the art for image-guided minimally invasive spine procedures. Back pain is a major health problem with serious economic consequences. Minimally invasive procedures to treat back pain are rapidly growing in popularity due to improvements in technique and the substantially reduced trauma to the patient versus open spinal surgery. Image guidance is an enabling technology for minimally invasive procedures, but technical problems remain that may limit the wider applicability of these techniques. The paper begins with a discussion of low back pain and the potential shortcomings of open back surgery. The advantages of minimally invasive procedures are enumerated, followed by a list of technical problems that must be overcome to enable the more widespread dissemination of these techniques. The technical problems include improved intraoperative imaging, fusion of images from multiple modalities, the visualization of oblique paths, percutaneous spine tracking, mechanical instrument guidance, and software architectures for technology integration. Technical developments to address some of these problems are discussed next. The discussion includes intraoperative computerized tomography (CT) imaging, magnetic resonance imaging (MRI)/CT image registration, three-dimensional (3-D) visualization, optical localization, and robotics for percutaneous instrument placement. Finally, the paper concludes by presenting several representative clinical applications: biopsy, vertebroplasty, nerve and facet blocks, and shunt placement. The program presented here is a first step to developing the physician-assist systems of the future, which will incorporate visualization, tracking, and robotics to enable the precision placement and manipulation of instruments with minimal trauma to the patient.**

***Index Terms*—Interoperative imaging, magnetic resonance imaging (MRI)/computerized tomography (CT) registration, medical robotics, minimally invasive procedures, spine, three-dimensional (3-D) visualization.**

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I. Introduction

BACK pain is the major source of chronic disability in the United States [1]. Each year, the treatment and loss of work associated with back pain have an economic impact in excess of $50 000 000 000 in the United States alone [2], [3]. Although open techniques of surgical repair and augmentation of the spine are widely practiced with good success, the comorbidities of open back surgery are serious and well documented. First, open back surgery requires extensive soft tissue dissection. Muscle retraction during surgery has been shown to do short term damage and to affect long term, degenerative changes [4]–[6], which increase the patient's susceptibility to reinjury [7]. Most of the recovery involved in open spinal procedures is due to the soft tissue dissection and muscle trauma involved [8]. This trauma incurred in open spinal surgery necessitates long recovery time and extended loss of work [2], [9]. Recovery from open spinal surgery exposes the patient to prolonged opiate analgesia. Pain management researchers agree that such analgesia poses a nontrivial risk of initiating, or exacerbating, addiction in the recovering patient [10], [11].

Minimally invasive approaches to spine surgery decrease tissue damage associated with open techniques. This has been shown to shorten hospital stay, speed recovery, lessen the long-term muscle wasting effects of open surgery, and spare the patient exposure to possibly addicting opiate medication. Together, these benefits promise to decrease the cost of treating spine disease while retaining the effectiveness of open approaches.

Minimally invasive spine procedures are rapidly growing in popularity due to improved techniques and decreased trauma to the patient [12]. Percutaneous spine procedures are a type of minimally invasive technique in which thin, tubular instruments are placed and then manipulated through the skin to treat a variety of spinal conditions. Percutaneous techniques for biopsy, vertebroplasty, nerve and facet blocks, laser and radiofrequency ablations, among others, are widely practiced [8], [13].

This paper reports on the development of a program in image-guided percutaneous spine procedures at the Imaging Sciences and Information Systems (ISIS) Center, which is a medical imaging group in the Department of Radiology at Georgetown University Medical Center [14]. This program is a multidisciplinary effort between engineers and physicians aimed at creating new techniques for image-guided spine procedures.

Several technical problems have been identified that must be overcome to advance the state-of-the-art in the field of minimally invasive surgery. These problems will be described in the next section, followed by a description of technical devel-

opments in progress to address these difficulties. The clinical investigations undertaken to evaluate these advances are then briefly described.

II. Technical Problems

While minimally invasive and image-guided techniques have already been developed in many institutions, some technological problems remain unresolved [15], [16]. Some of the principal obstacles to enabling image-guided, minimally invasive techniques include the following.

1) Optimal intraoperative imaging is not widely available: Percutaneous approaches to the spine depend on adequate imaging of underlying anatomy. Conventionally available fluoroscopic visualization does not provide a three-dimensional (3-D) image for precise targeting and path planning. Intraoperative CT allows adequate visualization of spinal bone and 3-D image capability.
2) CT and MRI spine images not concurrently available: CT and MRI spine images provide different information about bone and soft tissue structures, both of which are useful in planning and execution of diagnosis and treatment. Because CT and MRI images cannot be obtained concurrent with surgery at a reasonable cost, these images need to be registered into a single image that can be made available in the operating room.
3) Oblique paths cannot be visualized: 3-D visualization and graphical overlay of instruments in 3-D will allow oblique paths to a target that crosses several adjacent axial CT slices.
4) Tracking is limited: Percutaneous spine tracking is not available. Tracking of the spine and surgical instruments with a graphical overlay on medical images will allow path planning and path recording. Percutaneous spine tracking would allow precise intraoperative image guidance by correcting for intraprocedural spine movement.
5) Instrument placement slow and inaccurate: mechanical instrument guidance will assure accurate placement of instruments from the skin entry point to the target and increase the speed of minimally invasive surgery.
6) A software architecture for the integration of imaging, localization, and robotic instrumentation does not exist. Current surgical navigation systems employ proprietary software interfaces between fixed instrument types. A more flexible, component-based software framework for integrating technologies is needed.

While some of these problems have been solved in specific domains, there is still a great deal of work to be done. In our program, we intend to directly address these issues and plan to leverage the efforts of other researchers wherever possible to achieve a comprehensive approach to these problems.

III. Technical Developments

The long-term goal of our research program is to develop an integrated system to enable the next generation of percutaneous spine procedures. The equipment and techniques developed are intended to be transferable both to other classes of minimally invasive spine intervention (key-hole access and endoscopic procedures) and nonspinal percutaneous applications as well. As one of our first steps in this effort, we are assembling a robotic biopsy testbed to serve as a platform for development and integration. The technical developments that comprise the testbed include: 1) a mobile CT scanner; 2) MRI/CT image registration; 3) 3-D image visualization; 4) position tracking; 5) a small "needle driver" robot; and 6) software integration of the system components. These technical developments are intended to address the unresolved technical problems discussed in the preceding section. In addition to providing a framework for development, the testbed will be used to compare robotically assisted biopsy to the current manual technique. It will also allow us to investigate software architectures for integrating multiple medical devices. A system diagram is shown in Fig. 1. This work is part of our collaboration with the Urology Robotics Laboratory of the Johns Hopkins Medical Institutions, under the direction of Dan Stoianovici, Ph.D., and the Computer Integrated Surgical Systems and Technology (CISST) Engineering Research Center at Johns Hopkins University, under the direction of Russell Taylor, Ph.D. In the following sections, we will discuss each of the components of the testbed in some detail, and suggest how they contribute to enabling the next generation of percutaneous spine procedures.

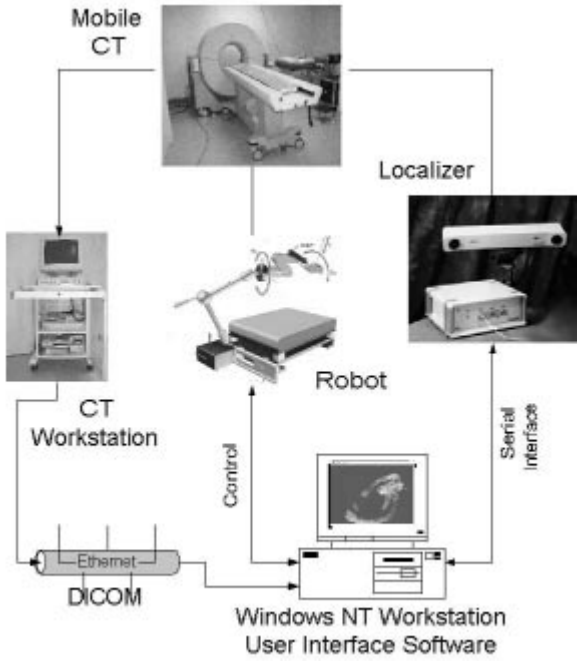


Fig. 1. Robotically assisted biopsy system concept.

A. Intraoperative Mobile CT

Accurate intraoperative visualization of spinal anatomy is a crucial element in enabling the minimally invasive, percutaneous spine surgery currently in development [16]. Precision in spinal procedures is critical because of the proximity to nerve roots and spinal cord. Any minimally invasive approach to the spine depends on high-quality imaging to negotiate this complex anatomy when the surgical opening is small. CT images of the spine provide more information about vertebral anatomy than images obtained with currently available intraoperative modal-

ities such as fluoroscopy or ultrasound [17]. Intraoperative CT promises to provide the interventionalist with a means to evaluate spinal anatomy, correct surgical path, and assess instrument placement. The accuracy of tip definition with new-generation CT machines is within 1 mm^3 [18], [19], which is considered sufficiently accurate for surgical planning and intraoperative targeting [20].

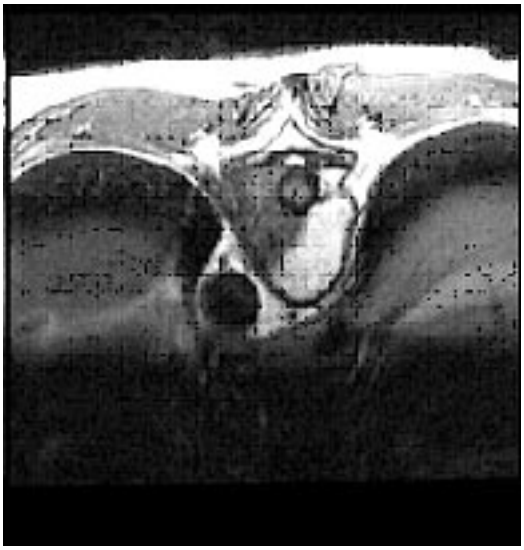
As an initial step in our research program, we have integrated a mobile CT scanner (Philips Tomoscan) to provide intraoperative images [21]. The first report of on-demand CT in an operating room setting was by Butler *et al.* [22], and intraoperative CT has since become available in several medical centers throughout the United States [23], [24]. At Georgetown, the mobile CT scanner has been used in interventional radiology, radiation medicine, and the operating room for spine tumor resection [25] and pediatric craniotomies [26]. The major procedures impacted by the availability of intraoperative CT are in interventional radiology and in neurosurgery. Since May 1998, the mobile CT has been used in more than 100 procedures at our institution. The CT scanner is an FDA-approved device. Since both the gantry and the table can move during scanning, the gantry can be used with the CT table (as done in the operating room) or with another table such as a fluoroscopy table (as done in the interventional suite).

In neurosurgery, we have used the mobile CT to provide support for complex open back procedures, particularly the treatment of craniocervical lesions and spinal cord tumors. In such cases, adequate visualization of the extent of tumor and the complex anatomy has proven instrumental in successfully removing adequate tumor tissue without incident. Our experience with neurosurgical spine patients shows that the use of intraoperative CT scanning changed the course of the surgery in six out of 17 cases [25]. CT proved beneficial in facilitating adequate ventral clival and craniocervical decompressions, assisting in more complete tumor resections, and verifying correct graft and instrument placement before surgical closing. We have also used the mobile CT extensively in neurointerventional radiology for adequate intraoperative guidance and postoperative assessment for vertebroplasty, biopsy, and nerve and facet blocks. Our experience with these procedures is detailed in Section IV, where we discuss clinical applications.

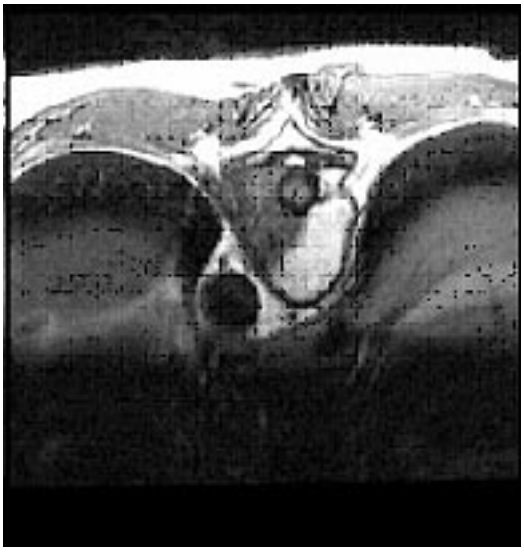
B. MRI/CT Image Registration

Percutaneous spine interventions require adequate knowledge of tissues in and near the target site of surgery. Currently, no single imaging technology is sufficient for imaging both bone and soft tissue adequately [15]. CT is best for visualizing bone and certain soft tissue structures. It also provides superior instrument tip visualization, which is critical when navigating in high risk areas, like the spine [19]. MRI is superior for imaging soft tissue and particularly in differentiating protruded discs from surrounding anatomy [17], [27]. It would be, for most sites, cost prohibitive to utilize MRI in the operating room except for the most critical procedures. Intraoperative CT is far less expensive and increases the practicality of intraoperative visualization.

Rather than relying on intraoperative CT and MRI imaging for image guidance, one goal of our research effort is to uti-



(a)



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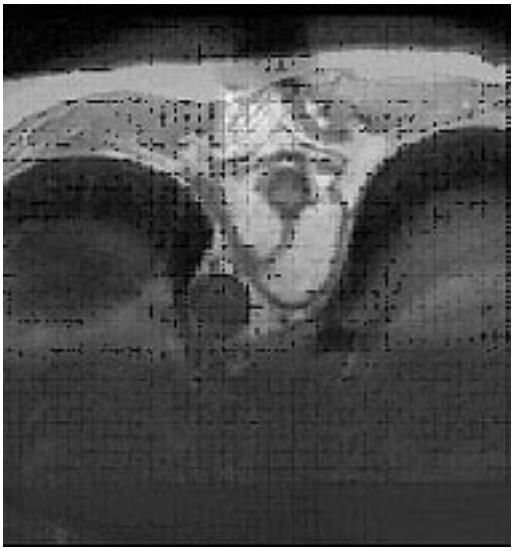

(c)

Fig. 2. Preoperative MRI and intraoperative CT registration (courtesy of L. Arata, Picker International).

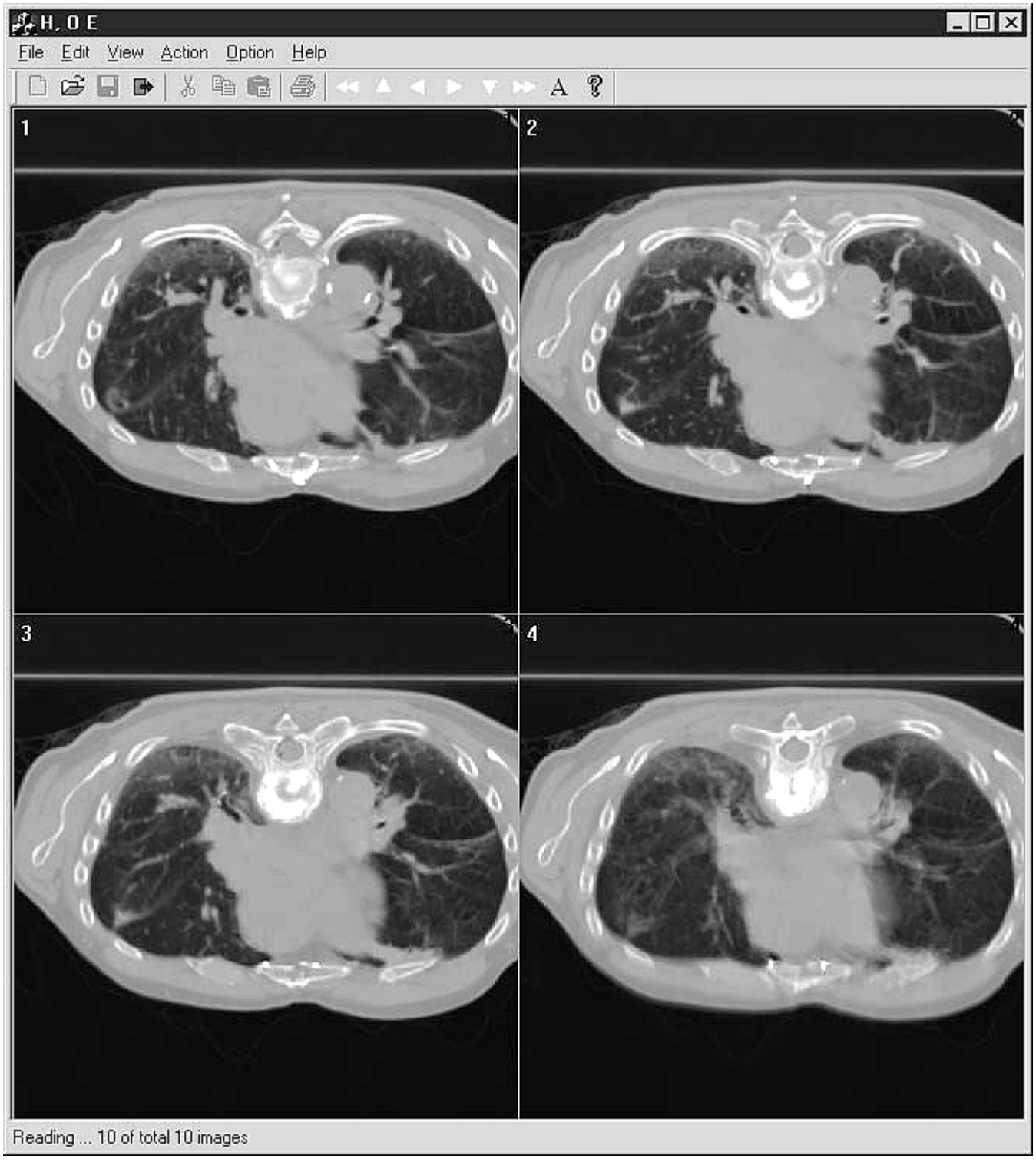

Fig. 3. Axial CT images.

lize registered, preoperative CT/MRI images. Image registration will allow us to fuse CT and MRI imaging data to permit visualization of soft and bony structures in a composite image. This offers the physician optimal visual information about the target anatomy. This fused image data might then be used to generate 3-D renderings of the anatomy to serve as a 3-D map for intraoperative surgical navigation [28], [29]. The use of preoperative images for surgical navigation requires the additional step of registering patient and instrument locations to the image. Intraoperative CT scans would then be used to verify instrument placement and surgical outcome if deemed appropriate.

Image registration for spine images is not currently a solved problem [30], [31]. There are basic registration programs available, but these do not correct for the slight shifting that can occur between two different vertebrae upon patient motion or in course of surgical manipulation. In collaboration with L. Arata

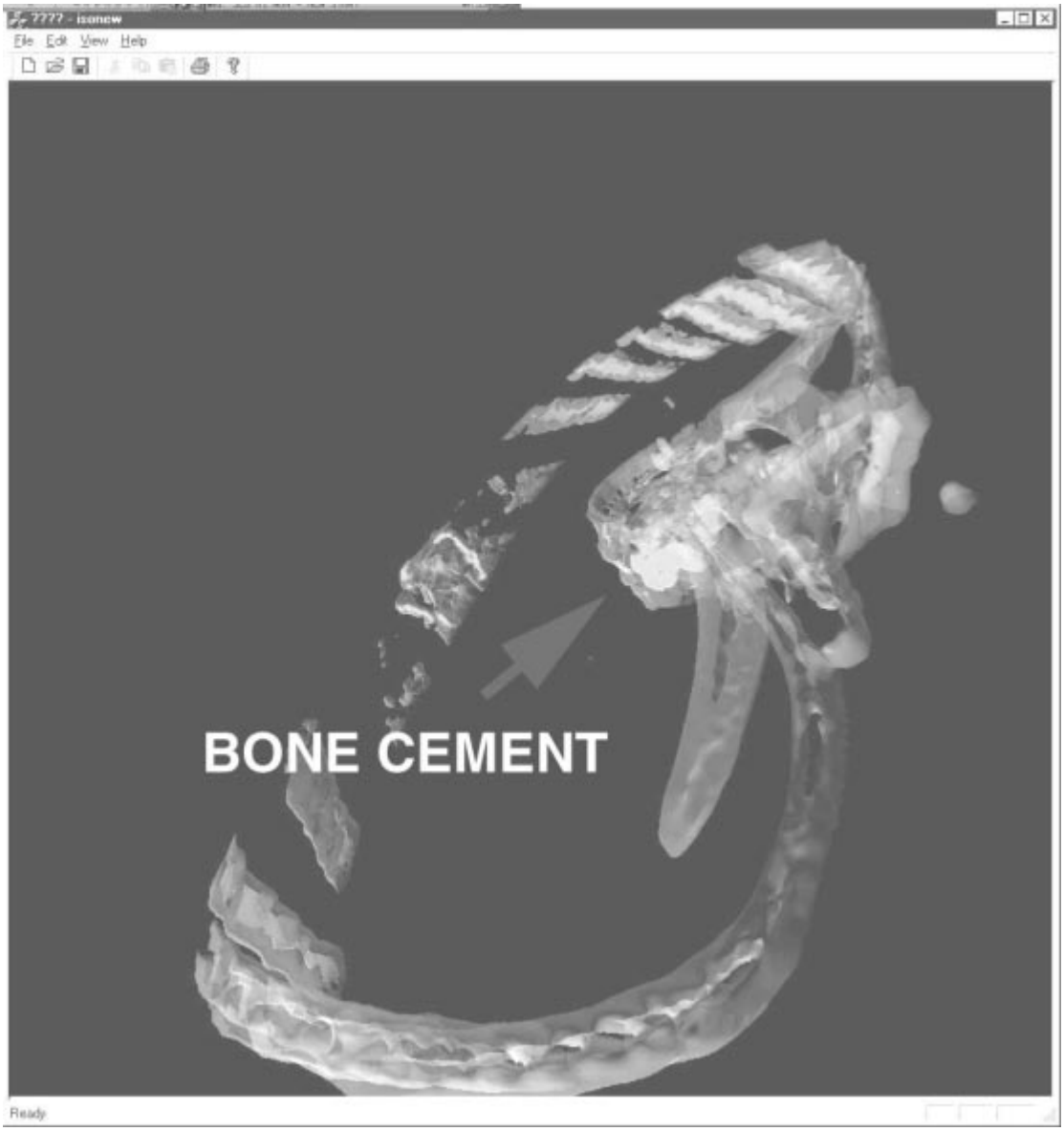

Fig. 4. 3-D rendering.

of Picker International, we have presented preliminary results on registration of CT and MRI images and an example registered image is shown in Fig. 2 [32]. In the initial stages of our program, we are relying on preoperative CT images to provide image guidance, with the intention of introducing MRI co-registration when our technical advances permit.

C. 3-D Visualization

3-D reconstruction of MRI and CT images of the surgical field may provide optimal information for surgical guidance and instrument manipulation in minimally invasive surgery. Using properly displayed 3-D images the physician will have adequate information about the relationship of the target abnormality to surrounding structures despite minimal surgical opening. This information will permit the physician to determine the best approach to the target tissue and make the most rapid and accurate decision about appropriate treatment. 3-D visualization is expected to be particularly helpful in planning and implementing oblique directions for the placement of instruments. As the importance of minimally invasive surgery increases, it is desirable that standards for obtaining, displaying, and analyzing 3-D images will develop, although currently no such standards exist [15].

3-D visualization in spinal surgery will permit the easier placement of instruments that cross from one imaging slice to adjacent slices, whether these instruments are needles being placed in vertebra or screws installed across facet joints for fusion. In spine decompression surgery, it will allow improved understanding of the interconnection and displacement of bony fragments and should allow improved methods for their removal or displacement. Initially, we plan to develop techniques for the intraoperative 3-D display of computed tomography (CT). Later, we plan to develop methods for the 3-D display of fused images incorporating preoperative MRI and intraoperatively obtained CT images.

As an initial study to demonstrate the utility of 3-D reconstruction, 3-D visualization software was developed to examine the spread of bone cement after vertebroplasty procedures [33]. This visualization software is part of a larger software package called the ISIS Center Spine Procedures Imaging and Navigation Engine (I-SPINE) [34]. The images for study were acquired by the mobile CT scanner. Offline, these images were then transferred to a Windows NT personal computer using the digital image communications in medicine (DICOM) standard. The I-SPINE software was then used to segment the bone cement and vertebral body based on histogram windowing (Fig. 3). The resulting images were rendered in 3-D for viewing by the interventional radiologist (Fig. 4). At the moment, only preliminary work has been done, but the interventional radiologist has stated that the images are useful for visualizing the spread of bone cement. Related research has also been done on developing improved visualization algorithms [35].

D. Optical Localization and Registration

In order to provide the physician with optimal information about the surgical field, and to assure maximum accuracy in a minimally invasive procedure, it is essential to pinpoint the locations of instruments, anatomical structures, and operating room landmarks in 3-D space and in relationship to one another. This process is referred to as localization or tracking. Tracking will permit matching, or "registration" of the surgical space to image space, as represented by preoperative MRI and CT images. Registration of image and surgical space allows the physician to use the registered image as a reliable 3-D "map" for operative planning and intraoperative guidance. This use of patient and instrument registration, while relatively new to spinal applications, is widely used in neurosurgery. These "frameless stereotactic" systems for intercranial localization and targeting are widely commercially available and have achieved high levels of accuracy [36].

Current techniques of percutaneous spine intervention, applied without instrument and spine tracking registered to image guidance, risk compromised accuracy for several reasons. First, individual and adjacent vertebrae have been shown to move substantially in relationship to one another during surgery due to breathing and surgical manipulation. Movement of up to 1.3 mm, peak to peak, has been reported from breathing alone, at the lumbar level [37]. Vertebral tracking and image guidance is considered the standard of care in pedicle screw placement, for example, because imaging alone has been shown to be insufficiently accurate [38], [39]. Without vertebral tracking and intraoperative image guidance, the interventionalist is required to rely on successive steps of needle placement, image verification, needle advancement, re-imaging, and so on until the target is obtained. This slow approach to the target increases the likelihood of intraprocedural patient movement and instrument shifting due to gravity. Percutaneous spine tracking may help eliminate these sources of inaccuracy and provide maximally precise targeting.

Several classes of tracking technology exist, each with attendant strengths and drawbacks. Optical, magnetic, mechanical, and ultrasonic position digitizers are available [40]. At Georgetown, we are investigating both optical and magnetic tracking systems for tracking of the spine.

Fig. 5. Hybrid Polaris (courtesy of Northern Digital, Inc.).

Fig. 6. Interventional phantom (CIRS, Norfolk, VA) with dynamic reference base (Traxtal Technologies, Bellaire, TX) attached.

The optical tracking system we use (Hybrid Polaris, Northern Digital, Waterloo, Canada) is shown in Fig. 5 and determines the orientation and position of tracked objects relative to a camera system. Objects are tracked by rigidly attaching retroreflective spheres or active infrared LEDs (IREDs). The spheres or IREDs can be detected by the camera system and used to determine the location and orientation of the object. The current version of the Polaris can track up to three active and three passive tools simultaneously and is controlled via the serial port of the host computer.

By attaching reflective spheres directly to the CT table, we are able to track the CT table and gantry. Similarly, tracking spheres located on the robot and end effector will enable us to directly monitor the robot position. This is especially important as a safety feature to verify the robot's own encoders. Finally, dynamic reference base tracking (DRB) as shown in Fig. 6 implanted percutaneously into vertebral bone will allow tracking of spine movement. Intraoperative tracking of spinal anatomy,

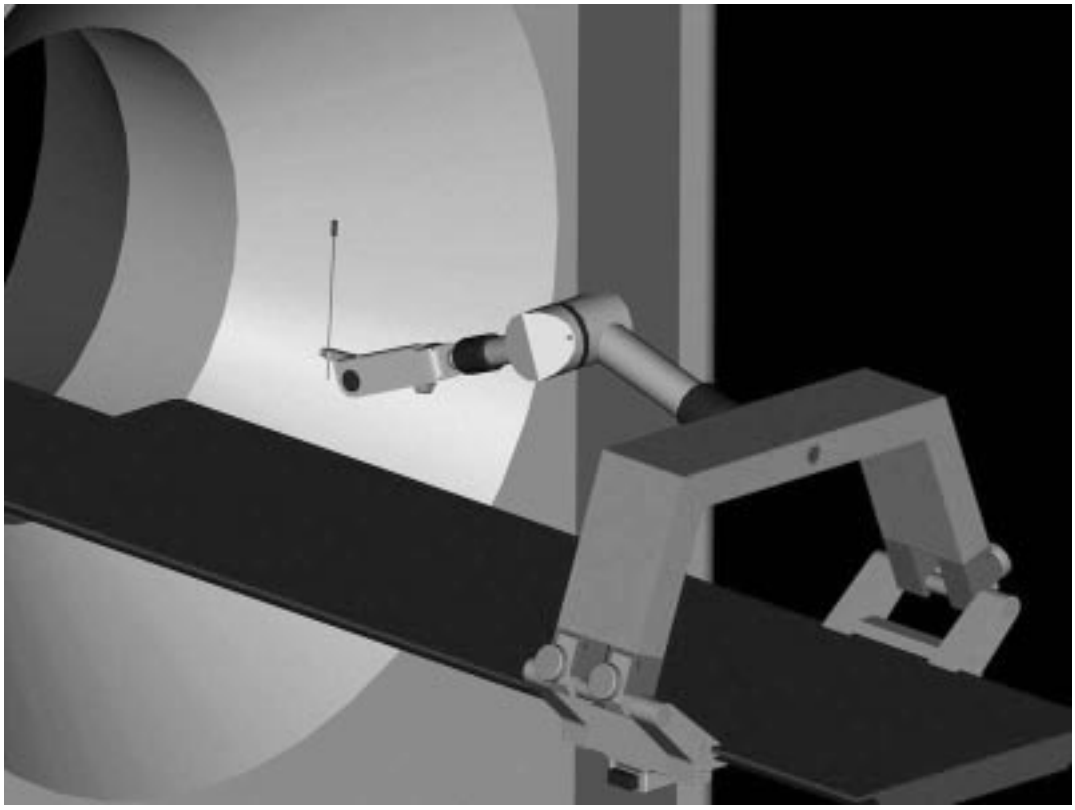

Fig. 7. CAD rendering of robot mount and arm on CT table.

the operative environment, and the robot end effector will allow for updated image registration and real-time image-guidance.

Optical tracking systems in general, and the Hybrid Polaris in particular, are characterized by a high degree of accuracy [41]. The major drawback of optical systems is the requirement that a "line of sight" between the trackers and the camera remain at all times. This line of sight requirement can be cumbersome and difficult to maintain in the delicate surgical environment, or when intraoperative imaging is required, and may reduce the acceptance of image-guided spine surgery among physicians [42], [43]. In an attempt to compensate for these difficulties, we are currently evaluating a soon-to-be commercially available magnetic position digitizer (the Aurora from Northern Digital). This tracker represents a new generation of DC magnetic trackers with increased accuracy and stability even in ferromagnetic environments [44]. Ongoing research work at our lab is dedicated to comparing the accuracy and resiliency of the magnetic system in comparison to the well-characterized optical system. The tracker's sensors are small (0.9 mm diameter) and potentially can be embedded into spinal bone, paraspinal tissue, or in catheters that can be placed inside the body. Besides the small size of the sensors, the other main advantage of magnetic tracking is that no line of sight need be maintained, which makes the tracking of internal anatomy possible.

E. Mechanical Guidance

Robotics were introduced into the surgical arena in the 1980s with the primary purpose of improving precision. Intracranial neurosurgical procedures were the major focus of the first robotic systems, in part because a high degree of precision is required for localization and manipulation within the brain, and because cranial anatomy provides relatively fixed landmarks. Medical robotics has since expanded to other clinical applications. Many prototype robotic systems have been developed, but presently only a few systems are available commercially [45], [46].

To the best of the authors' knowledge, there are no other research groups specializing in robotics for spine procedures. At Georgetown University Medical Center, we are developing a robot guidance system for percutaneous spine procedures in collaboration with the Urology Robotics Laboratory of the Johns Hopkins Medical Institutions and the Computer Integrated Surgical Systems and Technology Center of Johns Hopkins University. The system is aimed at increasing the precision and efficiency of instrument placement and manipulation during percutaneous spine procedures. We believe that this will lead to better patient outcomes, but this remains to be seen.

The robotic device will be based on the RCM-PAKY (Remote Center of Motion/Percutaneous Access of the Kidney) Robot, which has been developed at Johns Hopkins and applied to percutaneous access of the renal collecting system [47]–[49]. The robot, schematically represented in Fig. 7, consists of a passive positioning and supporting arm (the GRAY arm), an active remote center of motion orientation mechanism (RCM) and a radiolucent needle driver (PAKY). The device will be mounted over the CT table using a bridge fixture as shown in Fig. 8.

The overall system comprises 11 degrees of freedom (DOF). The first eight DOF are used for initial positioning of the robot in close proximity of the skin insertion site and firmly locked

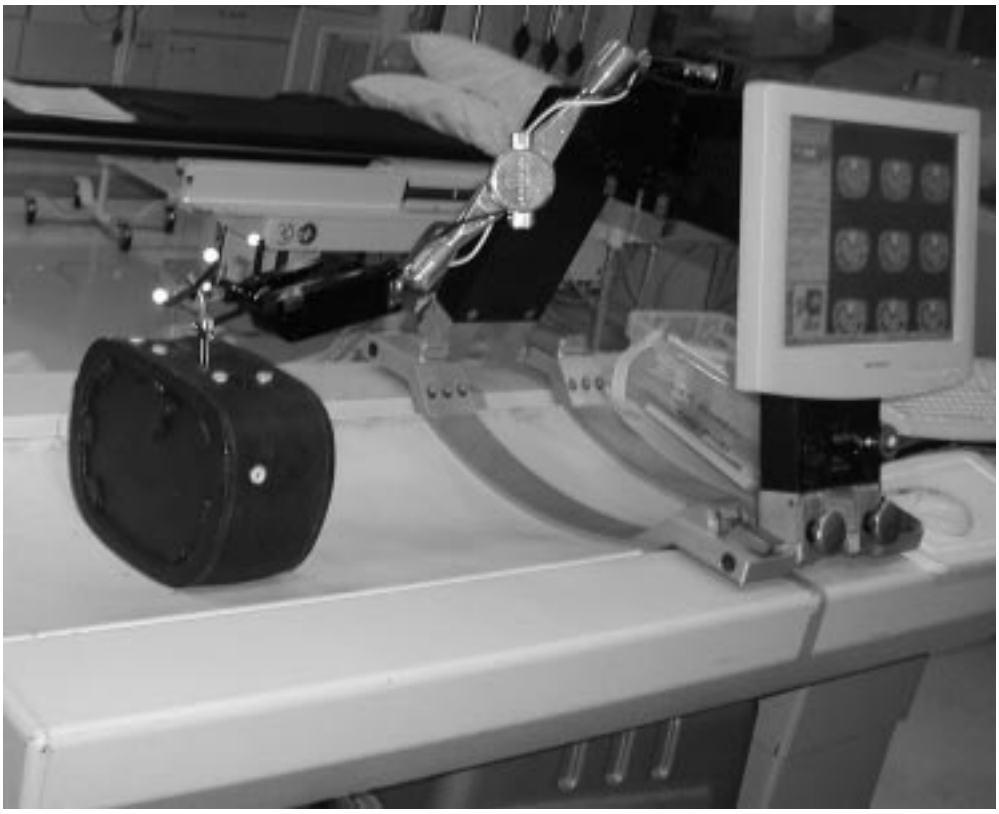

Fig. 8. Robot mounted on CT table and interventional phantom for testing.

during the operation. The remaining three degrees of freedom, implemented by the RCM robot and PAKY needle driver, are sufficient for orienting and inserting the needle at the desired target through the preset skin insertion point. The main advantage of this minimal kinematic architecture is the inherent safety given by the restricted mobility of the mechanical components. Moreover, separating the kinematics of orientation from needle insertion yields decoupled needle motion capabilities, thus further increasing safety.

The needle driver is constructed of acrylic plastic which is radiolucent and easy to manufacture as a sterile disposable part. Driver radiolucency is essential to image-guided procedures for providing unimpeded target visualization. Whereas the driver is sterilized, in clinical use the additional components of the system in close proximity to the operative site are covered with a sterile bag.

The robot accommodates joystick control for simple maneuvers and full computer control for the actual image-guided procedure. The electronic circuitry will be fully enclosed in the supporting bridge of the arm, so that the robot is self-contained and only requires a dc power supply.

The complete system is currently under development. The new design incorporates a major improvement over the first generations of the RCM robot, the "ball-worm transmission" recently developed at the Hopkins URobotics Lab [50]. This transmission fulfills the need for implementing simple and small no-backlash (no play between the input and output shafts) rotational transmission for miniature surgical robots. With this addition the RCM should exhibit superior motion tracking and positioning capabilities.

F. Software Integration

To analyze and manipulate the images used in this project, we have developed our own software package, called I-SPINE (ISIS's Spine Procedure Imaging Navigation Engine) as described in Section II [34]. I-SPINE is a Windows NT application, which is based on the Analyze/AVM libraries. The software architecture follows the Microsoft Foundation Classes (MFC) single document, multiple view paradigm. This has allowed the developers to add new visualization modules to I-SPINE that aid physicians in procedures outside the spine. These specialized applications have included 3-D visualization of bone cement for vertebroplasty and uterine fibroid embolization.

The I-SPINE software currently includes the following capabilities:

- DICOM receiver to accept images from mobile CT, fluoroscopy, and DSA units at Georgetown and elsewhere;
- two-dimensional (2-D) viewing of DICOM images (single slices or multiple slices up to 8×8);
- segmentation function based on volume histogram;
- multisurface 3-D visualization for applications such as vertebroplasty;
- registration of DSA images by manual pixel shifting.

Components of the operating room of the future will include some or all of the elements we have discussed: intraoperative imaging, 3-D visualization, image registration, tracking, and mechanical guidance. The integration of these components through software presents some unique challenges. From a software engineering perspective, the integration task requires

that an architecture be created that allows components to be introduced into (and removed from) the environment with minimal risk. These risk factors constrain the software architecture through complex requirements, such as quasireal time performance, fault tolerance, security, and quality of service.

Standards for software interfaces in medicine have been developed for data transfer (HL7) and image sharing (DICOM). No such standards exist, however, for integration of device control. We believe that the component-based software engineering (CBSE) approach developed in the computer science field can be used to create an architecture for medical device integration and control. CBSE is increasingly popular due to the explosive growth of the Internet and object-oriented analysis and design over the past decade. The vision of CBSE includes dynamic components that are described, located, and composed at run time to produce applications with the specific behavior that the user requires. This is a significant departure from the monolithic stand alone legacy systems of the past. Component-based software systems promise increased reuse, flexibility, and maintainability compared to their legacy counterparts.

CBSE is currently applied primarily to application domains that manipulate purely information products. In order to extend this application to device control and integration, appropriate levels of real-time performance, fault tolerance, security, and quality of service will need to be achieved. It is our belief, however, that the benefits promised by the CBSE approach can be applied to the problem of technology integration in surgical environments. We believe that the results will be a reduced cost of entry into the field to researchers and vendors alike, open platforms for robust integration, and systematic approaches to issues such as fault tolerance and quasi real-time performance.

For these reasons, we intend to apply CBSE practices to the integration of the technological developments outlined in this review. The mobile CT scanner, robot, tracking, I-SPINE visualization software, and image registration are conceived of as independent components to be integrated on a CBSE platform. Our goal is to provide an infrastructure that is scalable, efficient, fault-tolerant, and resilient to change. We hope to create an architecture that will allow the physician to choose and integrate precisely the components required for the procedure at hand. This will allow both the selection and integration of existing technologies in the operating room, and the incorporation of new technologies as they become available.

IV. Clinical Applications

Currently, percutaneous spine procedures are performed by freehand passage of instruments (such as a needle or trocar) from the skin surface to the spine. Based on imaging modalities such as X-ray fluoroscopy and/or computed tomography, the physician identifies the skin entry point and the target, thus defining the needle trajectory. The physician then aligns the instruments by hand and partially inserts it toward the target. The instrument is then released and the instrument position is checked with imaging to confirm proper targeting. As required, the physician may adjust the instrument in a free hand manner and then advance further. This process of "advance and check" is repeated until the instrument is adjacent to the targeted portion of the spine. The main problem with this approach is that the unaided human operator has limitations in accuracy when initially lining up the instrument and in staying on course. Additionally, when the physician lets go of the instrument, it may tilt out of alignment due to the effects of gravity, particularly when a large gauge trocar is used.

Strategies of image-guidance and computer assisted surgery, first developed for frameless stereotactic brain surgery [51], [52], have begun to impact this traditional mode of percutaneous spine work. However, acceptance of these strategies has been somewhat limited by several key remaining obstacles to their full implementation in the spine. In the following sections we will outline how the introduction of intraoperative CT imaging, 3-D visualization, patient and instrument tracking, and robotic assistance can contribute to overcoming the obstacles remaining to the implementation of image-guided percutaneous spine intervention. In particular, we will focus on the application of these technologies to percutaneous spine biopsy, vertebroplasty for spine augmentation, and nerve and facet blocks. The extension of these advances to nonspinal percutaneous procedures will be suggested in a technique of anterior intrahepatic portal shunt placement (a variation of the transjugular TIPS procedure). It is expected that image-guided technologies will also impact minimally invasive approaches to spine stabilization, nerve root decompression, and tumor reduction, among others.

A. Biopsy

The goal of our research program is to develop an integrated system to enable the next generation of percutaneous spine procedures. As a first step in this effort, we are assembling a robotic biopsy testbed to serve as a platform for technology development and integration. The previously discussed technical developments that comprise the testbed include: 1) a mobile CT scanner; 2) MRI/CT image registration; 3) 3-D image visualization; 4) position tracking; 5) a small "needle driver" robot; and 6) software integration of the system components. In addition to providing a framework for development, the testbed will be used to compare robotically assisted biopsy to the current manual technique.

Freehand percutaneous spine biopsy is a frequently performed alternative to open biopsy. Accuracy of this procedure is reported at 85–92% [53], [54]. This level of success diminishes considerably in inexperienced operators and in biopsy of precariously placed lesions [54]. Biopsy of the lumbar and thoracic spine report the highest levels of success and is the most routinely undertaken [55], [56]. Cervical spine biopsy is more difficult, with a higher rate of complication and lower reports of success due to the complexity of surrounding anatomy [57]. We believe that robotically assisted image-guided biopsy will be able to target and sample lesions with 2 mm^3 precision, exceeding the accuracy of the freehand technique [58]. We expect the rate of success to be higher for robotic biopsy of all spinal levels. Because freehand biopsy of the lumbar and thoracic spine is already quite successful, we assume that robotically assisted biopsy will prove most useful in enabling cervical spine biopsy and biopsy of anatomically precarious lesions.

We envision robotic biopsy would be carried out in the following manner.

1) Mobile CT Scanner and Operator's Workstation: The mobile CT scanner provides a series of axial images of the patient. Each image is 512 by 512 pixels, and a typical data set consists of from 10 to 100 images. The operator's workstation provides a graphical user interface to operate the scanner. The only interface to the outside world is a DICOM interface, where the images can be sent over a network to another DICOM capable system. In this testbed, after the scans are acquired, they are sent to a Windows NT workstation running our I-SPINE software.

2) 3-D Visualization and Path Planning: After CT imaging of the relevant anatomy is obtained, 3-D reconstruction and visualization is performed.

3) Patient and Instrument Tracking and Image Registration: Using optical and/or magnetic tracking, the patient's vertebral bone, the CT table, and the biopsy needle are located in real space. This digital representation of the operative space is then registered to the CT image, providing a 3-D "map" for path planning and targeting. Because the patient's movements are targeted in real time, this map will be continuously updated to reflect the true position of anatomy in image space.

4) Path Planning: The registered image and operative space, as represented by the workstation display, is used by the physician to plan the operative path. The target to be biopsied is identified. An appropriate path, avoiding sensitive intervening structures, is selected. This determines the appropriate skin entry point. Once the path has been planned, path information in the form of needle orientation and depth of drive are transmitted to the PAKY robot.

5) Robot: The robot will hold, automatically orient, and drive the biopsy needle in accordance with the physician's path plan. The robot is controlled by the NT workstation via a hardware and software interface.

6) Position Verification: A CT image is obtained to verify needle location and determine distance from target.

The testbed is currently under construction and initial trials are planned using an interventional phantom.

B. Vertebroplasty

The introduction of mobile CT and 3-D visualization into the interventional suite is impacting the performance of percutaneous vertebroplasty at Georgetown University Hospital. Percutaneous vertebroplasty involves injecting polymethylmethacrylate (PMMA, or bone cement) into the vertebral body. It is currently performed to strengthen vertebral bodies that have been mechanically weakened, or to relieve pain from spinal fractures, both traumatic and pathologic [59], [60]. Such weakening can occur in metastatic invasion of the bone [61], or osteoporotic degeneration [62], [63]. As its long term efficacy and results become known and studied, vertebroplasty is becoming a first-line treatment for spinal disease [64].

Most patients experience significant pain relief within 24 to 48 hours following the procedure. Exact mechanisms for pain relief are unclear. Proposed theories include: filling of vertebral microfractures, reduced intra-body movement, and damage to nerve root fibers from the exothermic reaction during cement curing [65]. While still a "new" procedure compared to traditional, open vertebrectomy, percutaneous vertebroplasty has emerged as a powerful minimally invasive tool for treating bony spinal disease. Mobility is achieved much sooner post-operatively, and with better residual vertebral stability than with the open procedure [64].

The current technique of vertebroplasty relies on fluoroscopy for intraoperative imaging. At Georgetown, we are using the mobile CT as needed to ensure precise needle placement and after the procedure to check for extravization. Extravization of PMMA, and embolization into the paravertebral venous plexus, is a rarely reported but serious complication of vertebroplasty [66], [67].

C. Nerve and Facet Block

Percutaneous facet and nerve blocks are another treatment modality that relies on minimally invasive techniques. In these procedures, patients are positioned prone as described above for vertebroplasty. An 18-to-22 gauge spinal needle is localized to the desired facet or dorsal nerve root region with fluoroscopy, and an injection of a long acting anesthetic (such as bupivicaine) and or a steroid (such as celestone) is performed following confirmation of extra-vascular needle tip position. Pain relief may be obtained from minutes to weeks after injection/ablation; relief, or the lack it, may help physicians better evaluate the cause of a patient's back and limb symptoms.

Low back pain without sciatica is often caused by degeneration of the facet joints [27]. About 80% of facet syndromes are located in L4/L5 and L5/S1. Surgical neurolysis of facet joints was introduced in 1971 by Rees [68] and was followed a few years later by electrocoagulation. Facet joint block with local anesthetic or facet joint denervation with 50–96% ethanol are performed at Georgetown University Medical Canter under intraoperative CT guidance. Treatment produces good results in 65–75% of carefully selected patients. Mobile CT is useful in facet joint blocks to monitor the positioning of the needle and the spread of ethanol or anesthetic to prevent errors of injection into nerve roots or vessels. The application of the full image-guidance and robotic assistance paradigm detailed in the biopsy testbed could further increase the safety and precision of this procedure.

Nerve root infiltration for nerve block or neurolysis requires extreme accuracy to fulfill its diagnostic and treatment purposes. Injection of anesthetic in the wrong location can cause blockade of adjacent nerves, muscle, and periosteum, with subsequent pain relief causing misidentification of the true cause of pain, and possible later mistaken neurolysis. Worse, injection of local anesthetic into a vertebral artery can cause convulsions immediately [69]. Negative aspiration is not enough to ensure safety in the absence of CT guidance [27]. One survey of freehand needle placement in nerve sheath infiltration showed inaccuracies of up to 3 mm^3, with extensive diffusion of anesthetic [70]. A high degree of precision and small quantity of injected anesthesia (0.5 cc or less) are desirable to optimize diagnostic utility. Studies emphasize the importance of placement as closely as possible at the affected nerve root. Intraoperative CT guidance is considered necessary in cases where more than one level is to be treated.

The application of mobile CT, patient and image registration, and robotic guidance for needle placement will increase the accuracy and effectiveness of the procedure. Mobile CT will ensure that critical structures are avoided and confirm that the target has been obtained before injection. Patient and image registration with spine tracking will permit preoperative path planning and precise targeting. Finally, the use of the robot to orient and drive the needle under physician direction will ensure the highest degree of accuracy and steadiness.

D. Transjugular Intrahepatic Portosystemic Shunt (TIPS)

TIPS creation is an increasingly important therapy in the management of portal hypertension [71]. In this procedure, a shunt is created between a hepatic vein and a portal vein, which is structurally supported by a metallic stent. This communication between the portal and systemic venous systems allows reduction of portal pressure and amelioration of the ascites, variceal bleeding, hepatopulmonary syndrome and other symptoms associated with portal hypertension [72].

TIPS creation can be a time consuming and technically challenging procedure. As typically performed, the shunt is created percutaneously from an internal jugular vein access. The hepatic vein to be employed is selected by standard catheterization. The target portal vein can be identified and targeted by several techniques including wedged hepatic venography, markers in the portal vein, or a combination of these techniques. Most often, however, the portal vein is successfully punctured after several blind passes with the Colapinto or similar needle. In difficult cases, this blind approach can result in fluoroscopic exposure of over an hour to the patient [72] and increases the likelihood of exposure to an errant transcapsular puncture [73], [74].

Our preliminary experience suggests that preoperative CT imaging can be used to plan and guide a TIPS procedure from an anterior percutaneous approach [75]. Placement of the shunt via this anterior approach requires modification of the TIPS procedure. Following simultaneous puncture of the target portal and hepatic veins, a guidewire can be passed from the portal into the hepatic vein. The wire in the hepatic vein can then be snared from the internal jugular vein access. A catheter would then be introduced in a normal anterograde fashion over the guidewire and slowly withdrawn under fluoroscopic guidance until the hepatic vein lumen is entered (catheter pullback technique). The wire is then advanced into the hepatic vein, creating a successful portal to hepatic vein tract. Ballon dilation of the tract and stent deployment are done in the usual fashion. Successful TIPS creation using this technique has been demonstrated in an *ex vivo* porcine model [75].

Our proposed version of the TIPS procedure relies on pre and intraoperative CT to plan percutaneous access to the target veins. Using a 3-D reconstruction of these images, the physician can determine an entry site with unobstructed access to the hepatic and portal veins. This path information, the preoperative CT, and the robot-guided instrument will be registered to patient anatomy using optical tracking technology and intraoperative imaging. The predetermined path plan will be transmitted to the robot, which can then, under physician control, obtain the hepatic and portal targets smoothly, precisely, and quickly.

This novel, anterior percutaneous approach to TIPS creation has several advantages. First, the risk of capsular puncture and intraabdominal hemorrhage due to blind puncture is minimized. There is less trauma to hepatic tissue overall because fewer puncture attempts will be required. Finally, radiation exposure to the patient and physician is minimized.

V. Summary

A program plan to advance the state of the art in image-guided minimally invasive spine procedures has been presented. The plan includes technology developments and clinical investigations. The goal of the program is to give the physician as much information as possible about the underlying anatomy, so the procedures can be successfully carried out through small incisions with minimal trauma to the patient.

This paper described some technology developments to improve the state of the art in image-guided and minimally invasive spine procedures. The importance of a strong collaboration between technical and clinical personnel cannot be overemphasized. Through teamwork, we believe this technology can improve clinical practice and lead to better patient care.

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