Robot-assisted Percutaneous Intervention in Open-MRI

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Motivation:

Image-guided surgical techniques have significantly advanced the field of percutaneous therapy in recent years, and have helped to improve the quality of diagnosis and treatment of cancer in particular. For example, with an estimated incidence of 220,900 cases and over 1,000,000 prostate biopsies performed in the United States in 2003 [Jemal-2003], effective screening and treatment methods are important. The definitive method for diagnosing prostate cancer is core needle biopsy, prompted by either an elevated PSA level or a palpable nodule. Transrectal ultrasound (TRUS) has been the "gold standard" for guiding biopsy, and most prostate therapies, due to its real-time nature, low cost, and apparent ease of use. However, studies have shown that TRUS-guided prostate biopsy misses the cancer in at least 20% of cases [Norberg-1997, Rabbani-1998, Wefer-2000], and that it is limited by a low sensitivity of 60%, with only 25% positive predictive value [Terris-1993, Keetch-1996].

MRI is an attractive choice for image-guidance, due to its high sensitivity for detecting prostate tumors, high spatial resolution, excellent soft tissue contrast, and multi-planar volumetric imaging capabilities. The peripheral zone (PZ) can be seen in T2-weighted images, and used to identify suspicious nodules in the peripheral zone. Multi-year clinical trials of MRI-guided prostate biopsy and brachytherapy are currently underway at BWH, using an intra-operative 0.5 Tesla MR imager (GEMS Signa SP) [D'Amico-2001]. While this work has established the technical and clinical feasibility for MRI-guided biopsy, the manual method of needle placement has remained unchanged. The use of a fixed needle template guide, with holes spaced 5mm apart, significantly limits needle placement resolution and constrains needle orientation. In addition, template registration and the manual computation and transcription of coordinates are prone to human error.

Materials and Methods:

We have developed a system that integrates an interactive planning interface with an MR-compatible robotic assistant that acts as a dynamic needle guide for precise, yet flexible needle placement. An MRI-compatible robotic manipulator was developed, in collaboration with the National Institute of Advanced Industrial Science and Technology (AIST) in Japan, for percutaneous interventions in open-MR, and is an essential component of the system described in this work. Its development marked the first comprehensive analysis of material and mechatronic compatibility of powered MRI-compatible surgical robots [Chinzei-2000]. The device (shown in Figure 2) consists of a three-degree-of-freedom Cartesian positioning stage and a two-degree-of-freedom orienting mechanism, and is mounted above the surgeon's head in the open MRI magnet. Two long rigid arms reach into the surgical space, and form a parallel linkage for manipulating an acrylic needle holder, or guide. The five motion stages are driven by ultrasonic motors (Shinsei USR-60N) attached to lead screws, and motion is measured by optical encoders with 10μm resolution (Encoder Technology, Cottonwood, AZ). A Flashpoint sensor is attached to the needle holder to provide independent redundant encoding.

This robotic device has been integrated with a software planning interface (built into the 3D Slicer, www.slicer.org), and a tracking and control system for percutaneous interventions in the prostate under MR-guidance. The physician interacts with the planning interface in order to specify a set of desired needle trajectories, based on anatomical structures and lesions observed in the patient's MR images. All image-space coordinates are computed and used to automatically position the needle guide, thus avoiding the limitations of the traditional fixed template guide. Once the needle holder is in position, the robot remains stationary while the physician manually inserts the needle through the guide and into the tissue, with real-time imaging for monitoring progress. This "point and click" methodology is illustrated in Figure 1.

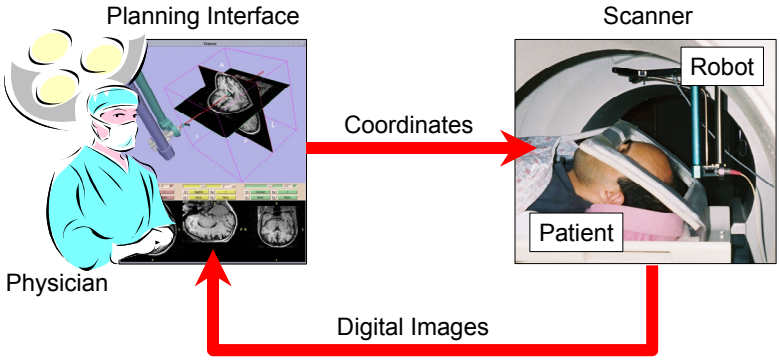

Figure 1: Image-guided intervention system with integrated planning interface and placement device.

Results:

This system has been tested extensively in phantoms and is currently being prepared for human trials. The MRI compatibility of the robot and all components was evaluated in a 0.5T intra-operative MRI scanner, and no adverse effects on image quality were observed. In fact, the robot was found to cause less field distortion than the body of the patient. In phantom trials, we used soft PVC models of the prostate and its surrounding tissues. Glass beads embedded in the prostate model were visible in the images, and served as targets for tests, as shown in Figure 2. With the image-guided system, we were able to place the needle tip within two millimeters of the target points during experiments.

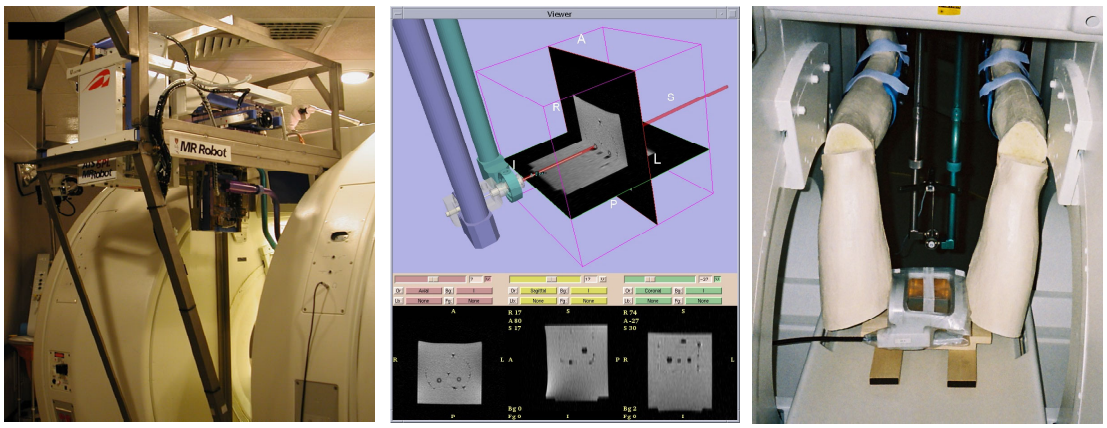

Figure 2: The robotic positioning device is shown mounted to the GE Signa SP (left). Needle trajectories are placed within the image volume using an interactive graphical interface (center). Phantom tests have evaluated placement accuracy and logistics (right).

Conclusion:

We have developed a planning and guidance system for percutaneous image-guided interventions, and have achieved encouraging results in phantom trials. An MR-compatible motorized positioning mechanism replaces the rigid needle template that is currently used for prostate biopsy and brachytherapy, thus providing enhanced needle placement resolution and the ability to guide needle trajectories at oblique angles. The "point and click" planning interface allows the physician to intuitively specify, visualize and revise needle placement plans directly in a graphical rendering of the patient's image volume, taken intraoperatively. The system is currently focused on prostate biopsy as a first application; however, the methodology is applicable to a variety of interventions in the abdomen and brain. We have endeavored to develop a system that is modular in design, so as to be applicable to multiple clinical applications and perhaps multiple imaging modalities in the future.

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