Technical Report

Virtual Simulation in Enhancing Procedural Training for Fluoroscopy-guided Lumbar Puncture: A Pilot Study

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Rationale and Objectives: Fluoroscopy-guided lumbar puncture (FGLP) is a basic procedural component of radiology residency and neuroradiology fellowship training. Performance of the procedure with limited experience is associated with increased patient discomfort as well as increased radiation dose, puncture attempts, and complication rate. Simulation in health care is a developing field that has potential for enhancing procedural training. We demonstrate the design and utility of a virtual reality simulator for performing FGLP.

Materials and Methods: An FGLP module was developed on an ImmersiveTouch platform, which digitally reproduces the procedural environment with a hologram-like projection. From computed tomography datasets of healthy adult spines, we constructed a 3-D model of the lumbar spine and overlying soft tissues. We assigned different physical characteristics to each tissue type, which the user can experience through haptic feedback while advancing a virtual spinal needle. Virtual fluoroscopy as well as 3-D images can be obtained for procedural planning and guidance. The number of puncture attempts, the distance to the target, the number of fluoroscopic shots, and the approximate radiation dose can be calculated. Preliminary data from users who participated in the simulation were obtained in a postsimulation survey.

Results: All users found the simulation to be a realistic replication of the anatomy and procedure and would recommend to a colleague. On a scale of 1–5 (lowest to highest) rating the virtual simulator training overall, the mean score was 4.3 (range 3–5).

Conclusions: We describe the design of a virtual reality simulator for performing FGLP and present the initial experience with this new technique.

Key Words: Radiology simulation; virtual reality; lumbar puncture.

INTRODUCTION

Lumbar puncture (LP) is a commonly performed medical procedure for a variety of indications. Fluoroscopy-guided lumbar puncture (FGLP) is usually performed if attempts at the bedside are unsuccessful. There is also an increasing trend to perform LP under fluoroscopy without prior bedside attempts, such as for patients who are obese or have a difficult anatomy because of a prior spine surgery (1–3). In addition to higher success rates, fluoroscopic guidance may reduce the incidence of traumatic LP (4).

Performing a successful FGLP requires a combination of anatomic knowledge and technical skill. Although the anatomic knowledge is typically gained through conventional didactic methods, acquiring the technical expertise traditionally requires performing the procedure on a patient under close supervision initially, followed by a gradual transition to independency. For a minimally invasive procedure such as FGLP, serious complications are fortunately rare (less than 0.5%) (5–7); however, performance of the procedure by an inexperienced operator requiring multiple attempts can be associated with increased patient discomfort as well as an increase in minor complications (8). Although cadavers have historically been used for procedural training, they are associated with increased costs and limited availability due to logistic problems of procurement, storage, and disposal. An alternative approach is using a physical task trainer in the form of a mannequin that can be modified to suit the purpose of training for LP. However, these devices have limited durability, and it may not be practical or cost-effective to create or purchase multiple models as may be needed to represent different case difficulty levels. Also, utilizing a mannequin in a fluoroscopy room during the simulated procedure requires additional personnel exposure to radiation and resource utilization.

Simulation technologies have been shown to serve as important educational tools in multiple specialties. In medicine, such an approach has been gaining more attention in the recent years as a way to gain new surgical skills, maintain competence,

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and minimize operative complications (9–11). Virtual reality simulation for FGLP has not been reported in the literature to our knowledge, and in this article, we describe the rationale, the technical specifications, and the construction of such simulator. This teaching tool may be invaluable to radiology training programs and may facilitate the process of acquiring technical skills and confidence without compromising patients' safety and comfort. Because technical performance of FGLP improves with training (12), we propose an effective virtual simulation of the FGLP that will help trainees become more familiar with the procedure before they perform it on patients. This simulation can also help radiology trainees formulate strategies to overcome some of the challenges associated with the procedure in a controlled environment away from clinical care. It would also be possible to modify this simulator to support more complex spine procedures, especially ones in which trainees receive little exposure, such as cervical punctures and epidural injections.

MATERIALS AND METHODS

The FGLP simulator attempts to virtually reproduce the following: (1) the anatomy of the lower torso, including the lumbar spine and adjacent soft tissues, both visually and through tactile or haptic feedback as the spinal needle traverses various tissues; (2) the spinal needle; and (3) real-time fluoroscopy for imaging guidance.

Virtual Fluoroscopy-guided Lumbar Puncture Module Design

The FGLP module was developed on the ImmersiveTouch platform (ImmersiveTouch, Inc., Westmont, IL), which is a commercially available procedural simulator using Sensimmer Mission Rehearsal software (ImmersiveTouch, Inc., Westmont, IL), which can digitally reproduce the procedural environment, including complex anatomy, on to a 3-D hologram-like projection. The images can be interacted with using a monitor-mirror system and haptic instruments, which provide tactile feedback (13). To create our FGLP module, we used anonymized computed tomography datasets from normal adult spines of optimal quality. The datasets were segmented to create the different components of the lumbar region, including the lower spine, the ligamenta flava, the posterior paraspinal muscle groups, as well as the overlying subcutaneous fat and skin. We also segmented the bony spinal canal. Different physical characteristics were associated with each tissue segment to replicate the tissues' degrees of resistance to the traversing virtual needle. These characteristics were refined using feedback from experienced neuroradiologists to mimic as closely as possible the real tissue characteristics. A 3-D model of the spinal needle was reconstructed as well. The model was then displayed as polygonal meshes and volumetric renderings. To simulate the image guidance part of the procedure, simulated fluoroscopic images were reconstructed from the datasets in the anteroposterior, lateral, and oblique planes.

Using the Virtual Fluoroscopy-guided Lumbar Puncture Module

At the workstation, the user holds a stylus representing the spinal needle and reaches in behind a half-silvered mirror (Fig 1, left image). A high-resolution 3-D image of the patient's back (Fig 2, left image) is presented to the user. The user wears an electromagnetic head-tracking device in addition to using the hand-tracking haptic device. This head-and-hand tracking allows stereoscopic interaction with the patient's displayed 3-D images.

The users begin with a brief tutorial on operating the system. They are then presented with a 3-D lower torso model that can be rotated by hand using a stylus, which also functions as the virtual spinal needle (Fig 1, lower right image). The virtual needle is attached to an arm with hinges, which allows the needle to be angled and moved in all directions. Using foot pedals, simulated fluoroscopic images can be reconstructed in real time in the anteroposterior and lateral planes. Using a separate button on the console, the virtual "tube" can be rotated to obtain oblique images. After the users determine the desired LP vertebral level and site, they can then direct the handheld virtual spinal needle toward the desired puncture site. Constant haptic feedback allows the user to feel the increasing resistance as the skin is tented, followed by the sudden "give" as the needle finally pierces the skin. If the needle needs to be repositioned, it can be pulled back, partially or entirely, and then readvanced. After piercing the skin and superficial soft tissues, the next major resistance is felt when the needle traverses the ligamentum flavum. Then, the user will feel a minor resistance as the spinal canal is entered to simulate the characteristic "pop." The bone is made impenetrable if inadvertently contacted, and a characteristic coarse sliding sensation is encountered over the surface of the bone. Simulated fluoroscopic images can be obtained at any time during the procedure, and the computer will project the needle on the simulated images so that the user can determine if the needle trajectory is optimal (Fig 2, center and right images). Once the users are satisfied with the location of the needle tip, they can choose to freeze the needle and use a dissection tool to virtually dissect away overlying tissues to visualize the exact location of the needle tip for educational purposes (Fig 1, top right image). The system can provide numerical feedback indicators, such as the number of needle passes, inadvertent bone contacts, fluoroscopy shots, as well as the distance of the needle tip from the set target site (thecal sac) (Fig 1, top right image).

Preliminary Data

After being briefly introduced to the system, five radiology trainees and a radiology nurse practitioner underwent the simulated FGLP training as part of an initial pilot study. Each trainee was given 30 minutes on the simulator, which included 15–20 minutes to be familiarized with the system features under the supervision of a facilitator followed by the actual simulation