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Handheld Real-Time Volumetric Imaging of The Spine: Technology Development

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Abstract

Technical difficulties, poor image quality and reliance on pattern identifications represent some of the drawbacks of two-dimensional ultrasound imaging of spinal bone anatomy. To overcome these limitations, we sought to develop real-time volumetric imaging of the spine using a portable handheld device. The device measured 19.2 cm x 9.2 cm x 9.0 cm and imaged at 5 MHz center frequency. 2D imaging under conventional ultrasound and volumetric (3D) imaging in real time was achieved and verified by inspection using a custom spine phantom. Further device performance was assessed and revealed a 75-minute battery life and average frame rate of 17.7 Hz in volumetric imaging mode. Our results suggest that real-time volumetric imaging of the spine is a feasible technique for more intuitive visualization of the spine. These results may have important ramifications for a large array of neuraxial procedures.

I. Introduction

Ultrasound imaging use has undergone a rapid expansion among anesthesiologists over the last decade. The ultrasound applications to anesthesia practice include peripheral nerve blocks, central venous line placement, peripheral intravenous cannulation, arterial cannulation, airway management and neuraxial procedures (1). Nowadays, epidural analgesia for labor or for postoperative analgesia is still performed using the “blind technique” i.e., without ultrasound imaging. The blind technique, although successful in many cases, may provide challenges in patients presenting with obesity, spine deformities, or previous back surgeries. In these patients, the blind technique can lead to repetitive attempts with increased risk of neurological complications (2). Awareness of these challenges has made ultrasound guidance a very appealing alternative approach (2–4). In this regard, techniques using ultrasound guidance have been investigated and several studies have demonstrated ultrasound’s efficacy for spinal and epidural anesthesia (5). However, the extension of ultrasound use to neuraxial procedures did not reach the same enthusiasm as for other indications and has instead generated some controversies (6). At least in part, these controversies are related to challenges associated with interpretation of conventional 2D

ultrasound image of spinal bone structures using ultrasounds systems that are engineered to image soft tissue. The result is that bone image quality is generally poor, which makes pattern identification arduous when visualizing landmark structures such as the vertebra (7,8). These effects are accentuated during obesity. Moreover, the vertebrae are a three-dimension anatomical structure, and therefore not visually amenable to two-dimensional imaging techniques. Karmakar et al demonstrated in a study of healthy volunteer that volumetric 3D ultrasound provided more detailed spatial anatomical information when compared to 2D ultrasound (9). This is of importance for patients with rotational spinal deformities. In this report, we determined that a real-time volumetric bone imaging technique within a handheld device is an attractive alternative to two-dimensional standard ultrasound imaging for neuraxial procedures.

II. Methods

A. Handheld ultrasound device description

A custom handheld ultrasound system for volumetric spinal bone imaging was designed and fabricated. A diagram of the physical prototype unit is illustrated in Figure 1 with a block diagram illustrating hardware function in Figure 2. The prototype hardware comprised two printed circuit boards (PCBs), a CPU carrier board, and an ultrasound board. The prototype device was completely self-contained and ran from a 3.7 V, 2380 mAh lithium ion battery. The CPU carrier board possessed a socket for a DM3730 computer-on-module (COM) board (Gumstix Inc., Portola Valley, CA), and supported an LCD touchscreen; debug port, two USB ports and power management (including battery charging). The power management unit took the battery power as input and provided power at different voltages and current capabilities to the CPU, XMOS microcontroller, and ultrasound front-end. The ultrasound board contained the ultrasound front-end circuitry for high voltage (HV) transmit and protection, a variable-gain-amplifier, 25 MHz, and 12-bit A/D converter. A high-speed USB connection between the ultrasound board and the CPU board provided bidirectional data and all required power. An XMOS microcontroller acted as a real-time processor for the ultrasound board and provided two primary functions: control of transmit, receive, and other functions of the ultrasound front-end; buffer received ultrasound data and otherwise act as a mediator between the ultrasound front-end and camera with the CPU. Imaging was achieved using a single element mechanically sector-scanned (60°) transducer at 5 MHz center frequency with approximately 70% –6 dB fractional bandwidth (Interson, Pleasanton, CA). A single element transducer was chosen over a typical linear array due to the mitigation of bone-derived artifacts (7) combined with reduced channel count and power consumption. In order to acquire volumetric imaging data, a cell-phone class CMOS camera was integrated into the device in QVGA portrait (240 x 32), 8-bit gray scale mode with automatic exposure and gain controls enabled. Overall dimensions of the device were 19.2 cm x 9.2 cm x 9.0 cm. All hardware specifications recited above were verified, using a combination of electrical measurements and software data collection, including recorded echo data in known conditions, *i.e.* wire target in water tank or tissue-mimicking phantom.

The ultrasound prototype system was configured to perform three-dimensional spinal bone imaging using a “free-hand” three-dimensional imaging technique (10–14) coupled with

bone detection as described more rigorously in Owen *et al* (15). Briefly, in free-hand 3D imaging, the 3D set of imaging data is acquired by compiling multiple two-dimensional ultrasound images as the device is physically scanned across the imaging surface. Each frame of data is placed within the 3D volume using position estimates associated with each frame. In our design, position estimates were achieved using a new approach based on analysis of the ultrasound frames (see Owen *et al* (15)) combined with estimates from the CMOS camera. In order to achieve bone-specific 3D imaging, a bone extraction filter was applied prior to contour filtering and rendering of graphics primitives using a 3D graphics programming interface for embedded systems (OpenGL ES) in real-time.

B. Experimental description

Experiments were performed to verify key system specifications and to demonstrate feasibility of real-time volumetric imaging of the spine with a handheld battery-powered ultrasound system. Quantitative measurements were performed to assess battery life and real-time frame rates at which volumetric imaging could be performed on the ultrasound prototype described above. For battery life experiments, a stopwatch was used to time the extent of continuous imaging that was achieved from a full battery charge to battery drainage and device shutdown. Measurements of system frame rate were quantified by observing the computational time required to perform all signal processing operations to render an image to the device display. The computational times were read out from the debug console onto a laptop computer during imaging with both 2D and volumetric (3D) imaging modes.

Feasibility of real-time volumetric spinal bone imaging with a handheld ultrasound system was assessed by visual inspection during a scan session using a tissue-mimicking ultrasound phantom. The tissue-mimicking ultrasound phantom was constructed by CIRS (Norfolk, VA) using a commercially available 3D printed CAD model of the L2–L4 lumbar spine region (3D Systems, Rock Hill, SC). This model has been used previously for assessment of free-hand volumetric imaging performance (15). The phantom consisted of tissue mimicking material Zerdine® with attenuation matched to the human liver at 0.5 dB/cm-MHz. The spinous process of the lumbar spine model was placed approximately 4.5 cm deep in the phantom.

III. Results

Experiments demonstrated a device battery life of 75 minutes during continuous imaging. Computational times recorded over 10 runs in 2D imaging mode averaged 35 ms (standard deviation 1.6 ms) indicating an average frame rate of 28.6 Hz. In free-hand 3D mode, the average computational time was 56.5 ms (standard deviation 8.6 ms) indicating a slower frame rate of 17.7 Hz.

Feasibility demonstration of volumetric spine imaging was achieved in real-time on the handheld ultrasound device. Figure 3 illustrates the device imaging in 2D mode under conventional ultrasound image reconstruction (Figure 3A) and after applying the bone extraction filter (Figure 3B). Volumetric real-time imaging is demonstrated in Figure 4 and in the supplemental video file [see video file]. The volumetric image data was acquired by

scanning the prototype along the phantom surface. The color mapping depicts the bone surface depth at all rendered locations with yellow-gold depicting more shallow surfaces while red-black depicts deeper bone structures. With Open GL ES tools and the touchscreen interface, the volume could be rotated with a finger swipe. Zoom in and zoom out was achieved with user interface buttons on the touchscreen.

IV. Discussion

The use of ultrasound has gained popularity among anesthesiologists, however, its use for neuraxial anesthesia has not reached the same degree of enthusiasm as for peripheral nerve blocks (6). This could be attributed to many factors. Firstly, sonographer skills, experience and comfort with the ultrasound machine and matching the correct probe design for a given clinical application is primordial. Secondly, reliance on pattern identification, although desirable, is in itself a drawback of two-dimensional ultrasound of the spine. Indeed, standard ultrasound systems are engineered to image soft tissue rather than bone structures, with the consequence that bone is imaged poorly. Ultrasound images are often degraded by a number of noise sources including speckle noise, reverberations and off-axis scattering, particularly when bone is present, making visualization of bone anatomy features arduous (7,8). This phenomenon is accentuated in obese and morbidly obese patients, where fat tissue interposition and bone depth results in image degradation from attenuation and phase aberration (16–18). Lastly, teaching two-dimensional ultrasound of the spine has been fraught with difficulties. Indeed, Margarido *et al*, found that ultrasound learning curves among anesthesiologists are not straightforward and pattern identification alone is not enough to achieve competencies (19). Recently, a remarkable improvement has been achieved in teaching ultrasound skills using an online three-dimensional model. In this study by Niazi *et al*, residents randomized to a three-dimensional online module identified key bony structures better than the control group during pre-procedural two-dimensional ultrasound albeit; no statistical difference was achieved among the groups (20). In our technology development efforts, we have determined that real-time volumetric imaging of a spine model using a custom handheld device is achievable and is a viable innovative technology. This proposed device has multiple intended uses. Its primary use is to aid with procedures on the neuraxis such as epidural injections, spinal taps, spinal anesthesia, and epidural analgesia/anesthesia. The device is expected to be particularly useful in patients with difficult anatomy such as patient exhibiting obesity, morbid obesity, patient with spinal deformities, and those with previous spine surgery. Other applications of the device can include use as a teaching tool, description of anatomical structures, and to enhance spatial visualization of the spine.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.
A depiction of the physical handheld ultrasound prototype device with labeling of key device components.

Figure 2. A block diagram illustrating connectivity and function of the handheld ultrasound prototype hardware.

Figure 3.

Figure 3A: Device imaging under standard 2D processing before applying bone extraction filter

Figure 3B: Image after bone extraction filter

Figure 4.
Volumetric real time image