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AREA: An Augmented Reality system for Epidural Anaesthesia

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***Abstract*— *Purpose:* Spinal needle injection procedures are used for anesthesia and analgesia, such as lumbar epidurals. These procedures require careful placement of a needle, both to ensure effective therapy delivery and to avoid damaging sensitive tissue such as the spinal cord. An important step in such procedures is the accurate identification of the vertebral levels, which is currently performed using manual palpation with a reported 30% success rate for correct identification. *Methods:* An augmented reality system was developed to help identify the lumbar vertebral levels. The system consists of an ultrasound transducer tracked in real time by a trinocular camera system, an automatic ultrasound panorama generation module that provides an extended view of the lumbar vertebrae, an image processing technique that automatically identifies the vertebral levels in the panorama image, and a graphical interface that overlays the identified levels on a live camera view of the patient's back. *Results:* Validation was performed on ultrasound data obtained from 10 subjects with different spine arching. The average success rate for segmentation of the vertebrae was 85%. The automatic level identification had an average accuracy of 6.6 mm. *Conclusion:* The prototype system demonstrates better accuracy for identifying the vertebrae than traditional manual methods.**

Keywords: augmented reality, panorama ultrasound, image guided intervention, interventional ultrasound.

I. INTRODUCTION

Epidural analgesia and anesthesia are commonly used in obstetrics for labour and cesarean delivery, and for surgery. Epidural procedures are effective alternatives to general anesthesia [10], especially in the parturient patient. In these procedures selection of the puncture site, which is usually between L2-L3 or L3-L4 for epidurals, and the needle angle are achieved through manual palpation of the spine. The challenge is to place the needle tip accurately in the targeted epidural space on the first attempt, thus reducing the procedure time and additional pain to the patient. While some of these procedures are performed for non-obstetric indications under fluoroscopic guidance, the majority of them are done blindly with manual palpation. Therefore, they are performed on parturient patients where exposure to ionizing radiation is contraindicated. This method correctly identifies the vertebral spaces in only approximately 30% of the cases [14]. Recently, a number of solutions have been proposed with the goal of reducing the radiation dose and increasing the needle placement accuracy, while maintaining or improving patient safety and reducing complication rates [2], [7], [19].

An imaging modality that has enjoyed a recent resurgence for guiding spinal procedures is ultrasound, which provides a more accessible, portable and non-ionizing imaging alternative to fluoroscopy. The success rate of conventional ultrasound for the identification of vertebral levels have already been shown to outperform the current standard of care which is manual palpation (71 % vs. 30 %, respectively [2]). To further improve the success rate, the acquisition of panorama ultrasound images has been proposed for the purpose of automatically identifying the vertebrae [8]. The authors reported an accuracy of 11.8 mm. While this accuracy could be sufficient for the identification of vertebral levels, robust and fully automatic identification of vertebral levels from panorama ultrasound images has remained a challenge. Furthermore, there is still a misconnect between the location of the identified levels of the panorama on the computer monitor and the patient's back. What is needed is a system that can: (1) automatically identify the vertebrae in the panorama image, (2) allow a small amount of subject motion between the ultrasound scan and the selection of the puncture site for needle insertion, (3) seamlessly relate identified levels to the patient's back, and (4) provide a clinically acceptable level of accuracy with respect to the patient's back, which is half the interspinous gap when the purpose is correct identification.

This paper makes two major contributions: Firstly, it presents a fully automatic and efficient lumbar level detection algorithm from panorama ultrasound image. Secondly, it presents an Augmented Reality system for Epidural Anaesthesia (hereafter referred to as AREA) that overlays the detected level on the live video image of the patient's back. We demonstrate that AREA can reliably identify and display the lumbar levels relative to the patient's back despite significant shadowing artifacts and variability of the spine's appearance in ultrasound images, as well as unavoidable minor patients movement and changes in spine arching. AREA aims to work within the established clinical workflow and setup, and increase the confidence of the operators to reliably identify the correct puncture site for epidural injections. It is intended to be easily used by operators with little ultrasound experience (i.e. many anaesthesiologists). This system could also be further developed with 3D ultrasound. This would provide volumetric panorama which, in turn, provide more data for vertebra detection but at greater computational expense.

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II. Materials and Methods

AREA consists of a SonixTOUCH ultrasound system (Ultrasonix Medical Corp., Richmond, Canada) equipped with a 6.6 MHz linear array transducer, a trinocular MicronTracker motion tracking system (Claron Technology Inc., Toronto, Canada), and a computer monitor displaying a graphical interface. Figure 1 shows an overview of the system. Initially, a marker, tracked by the Micron Tracker, is affixed to the patient's back close to the approximate puncture site, but outside the sterilized area. Tracked freehand 2D B-mode ultrasound images are acquired in the parasagittal plane (Figure 1) by attaching a second marker on the transducer. The images displaying the vertebral laminae are automatically registered to create a panorama ultrasound image of consecutive vertebrae. Using an automatic segmentation technique, the vertebral levels are identified. The information is then overlaid on the video obtained from the patient's back by the Micron Tracker, which is subsequently sent to the graphical user interface. As an easily reconfigurable software platform, AREA is built upon existing open-source toolkits such as the Public software Library for Ultrasound (PLUS) [9], 3D Slicer [3], Insight Toolkit (ITK) [5] and Visualization Toolkit (VTK) [15].

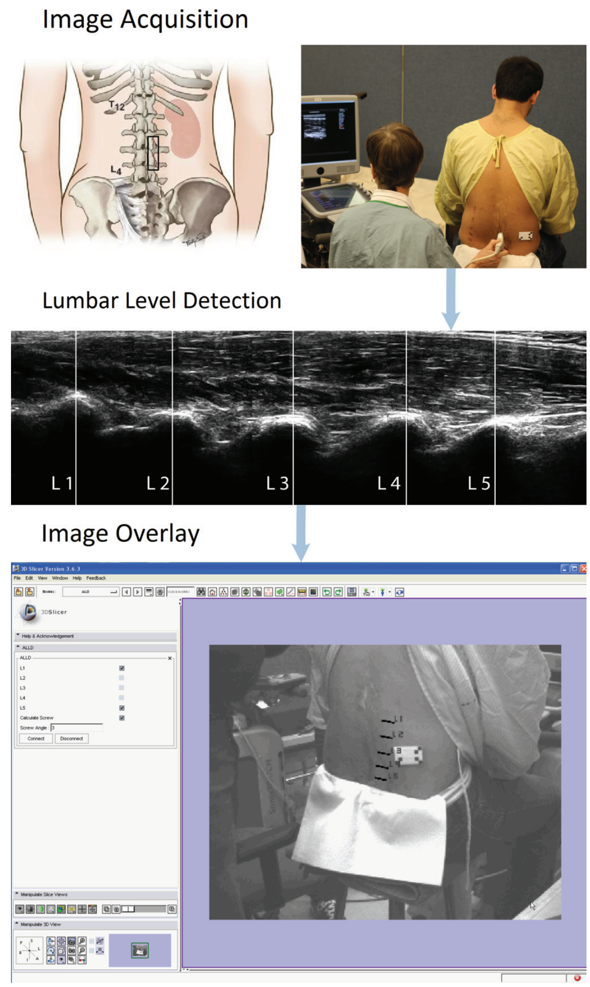

Fig. 1. System operation. Tracking information, video and ultrasound images are acquired using the Micron Tracker and ultrasound machine by using a tracked transducer. The system then generates a panorama image from the sequence of ultrasound images. After generating the panorama image, the system detects the lumbar levels and augments the video images with the labelled level. The final step is to send the images to the GUI. The top left image is used by permission of Anesthesia and Analgesia [18].

A. Image Acquisition

B-mode ultrasound images are acquired using a calibrated ultrasound transducer tracked by the Micron Tracker. We used the N-wire calibration method integrated within PLUS for this purpose [1]. Subsequently, a panorama image is generated by stitching a sequence of partially overlapping images acquired in real time. This is done by placing the transducer in the parasagittal plane at the L5-S1 intervertebral space. This obtains an image that includes both the space and the superior margin of the sacrum. Then moving the transducer superiorly across the laminae from L5-S1 to T12-L1, images are obtained from approximately the same paramedian plane. Individual images that overlap by at least 50% are stored by the sonographer using a foot pedal whenever the optimal image is observed at each level.

The stitching process uses the transformation between images and a rigid registration based on normalized cross correlation. Therefore, the tracker provides an initial guess for the feature alignment followed by a standard cross-correlation for final alignment. Such an approach allows a smaller search space for the alignment parameters and less likelihood of large misregistration errors (e.g. one vertebra to its neighbour). While this process may be susceptible to errors associated with out of plane motions of the transducer, it should be sufficient for the purpose of vertebral level identification, under the proposed scanning protocol. An example panorama image is shown in Figure 2.

B. Lumbar Level Detection

After generating the panorama image, the lumbar level is detected using an automatic image processing technique. A method to automatically detect lumbar levels was developed previously [8]. That algorithm used a median filter to first remove speckle noise and then used two other filters. One filter along each scan line highlighted bone edges and a second sinusoidal filter (with a period of a vertebra) in the image along the spine highlighted vertebral spacing. Then the vertebra location was detected by a least-squares fit of a parabola to each highlighted lamina. In this paper, a simpler method is implemented which produces results at least as accurate as [8]. The main difficulty in labelling the lumbar levels arises because ultrasound images have low resolution, speckle noise, low contrast, discontinuity, and uncertainty in the boundaries. These limitations impose extra difficulties in automatically identifying the lumbar levels. Moreover, the appearance of vertebral echoes and shadows are variable, depending on the patient and imaging plane, which is intended to be the parasagittal plane 10 mm away from midline, as shown in Figure 1. Therefore, a filtering and segmentation procedure is performed as explained in the following sections:

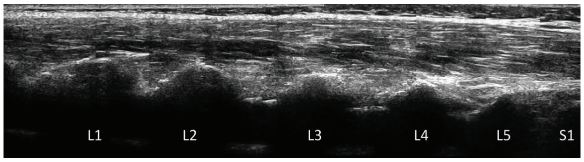

Fig. 2. Example of ultrasound panorama image obtained in the parasagittal plane, showing L1 to S1 from left to right as identified by sonographer

1) Panorama Preprocessing: The goal is to reduce the effect of speckle and increase the robustness of image segmentation to various artifacts in the image. Initially, we used a median filter to reduce the effect of speckle in the panorama image. Next, a bilateral filter [17], designed to smooth images while preserving edges, was used to reduce the interclass variance (pixels which belong to edges and pixels which belong to shadow area) and maximize the outer class variance (The difference between the edges' class and shadow's class).

The next step aims to identify the approximate width of each vertebra in the panorama image. One would expect that given the high reflection of the ultrasound beam from the bone surface, the vertebral surfaces could be detected using a simple image thresholding technique. For example, Kerby at al [8] used such a technique by zeroing two thirds of the pixels with the lowest intensity. However, as it has been reported by several researchers, reliable detection of bone surfaces in ultrasound data is challenging [4] [6]. Furthermore, in clinical ultrasound data, the bone surface may be poorly visible when the beam direction is at a large angle to the bone surface. However, in AREA, the focus is on determining the level of each vertebra in the panorama ultrasound image, rather than accurate segmentation of the vertebra surface itself. As such, we take advantage of the unique signature of the vertebra image in the ultrasound data (i.e. the shadow that appears under the laminae) and aim to segment this signature from the panorama images. Given the variable image intensity, we used an automatic thresholding technique based on Otsu's method [11]. This method assumes that the image contains two classes of pixels: foreground (i.e. the soft tissue and laminae) and background (i.e. the shadow underneath each lamina). Then, it calculates the optimum threshold separating those two classes so that intra-class variances are minimal.

2) Vertebra Detection: Panorama images show a specific periodic appearance of the laminae in the lumbar spine. We take advantage of this property to convert the two-dimensional panorama image to a one-dimensional signal. The panorama image is traversed along each column from the bottom of the image towards the transducer. Whenever a value above Otsu's threshold from the previous step is reached, the index value is used as a sampled point in the one-dimensional signal. Following a one-dimensional median filter of the signal, a peak detection technique is used to identify the peaks in the signal. These peaks approximately correlate with the middle section of the laminae in the panorama ultrasound image as shown in Figure 3.

C. Image Overlay

In order to provide the anaesthesiologist with an intuitive interface that matches the segmented panorama image with the view of the patient's back, we used 3D Slicer to display an augmented video feed from the Micron Tracker with the segmentation information. We used a volume ray casting method to create the overlay effect. Passing a 3D point coordinate in the camera space to the MicronTracker SDK will return the (x,y) pixel location on the camera image plane, representing where the ray from the camera viewpoint to the 3D location intersects the camera image plane. Hence, for each segmented lamina, we transform the segmented line to the 3D coordinates of the marker affixed to the patient's back and used the ray casting method in the Micron Tracker SDK to overlay segmented lines on the live camera view. Such a method avoids the possible parallax errors from augmented reality projections. The images are transferred in real time to 3D Slicer through OpenIGTLink, which are displayed to the anaesthesiologist on a standard monitor. Given that the camera tracks the position of the patient's marker, if the patient moves, the position of the overlaid lines is automatically updated. This rigid transformation step is expected to provide results within acceptable error tolerance of the epidural anaesthesia, if the patient's motion and changes in the spine arching are small. In the experiments to follow, we aim to determine the accuracy of the overall system under a range of realistic patient motion.

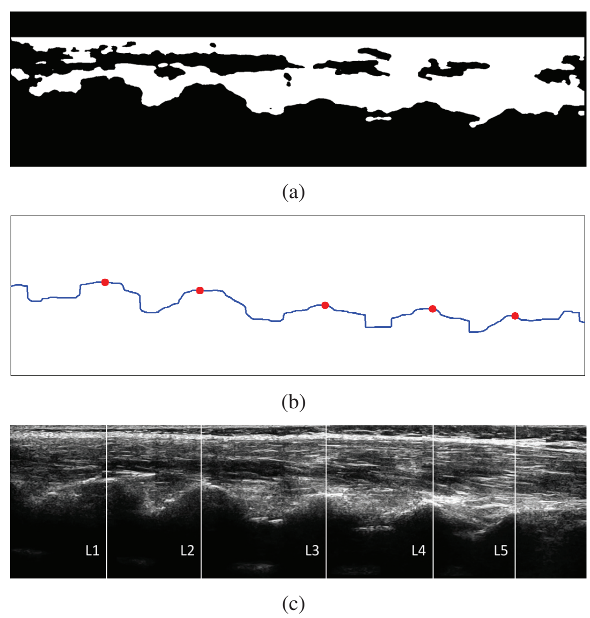

Fig. 3. Lumbar Level Detection Steps. (a) An example of a segmented panorama image after applying Otsu's method. (b) One dimensional signal, which is generated from segmented image, after applying a one-dimensional median filter and peak detection (red dots correspond to peaks in the one dimensional signal which correlate to vertebral levels). (c) An example of a segmented panorama image obtained in the parasagittal plane, detecting L1 to L5, from left to right.

TABLE I

THE RMS, MEAN AND STANDARD DEVIATION ERROR FOR AREA AGAINST SONOGRAPHER MEASUREMENTS. UNITS ARE MILLIMETRES, N=10.

Metric	L1	L2	L3	L4	L5
RMS	9.1	7	4.6	6.5	4.5
Mean	7.5	5.3	3.8	4.0	2.9
Std	5.5	4.8	2.8	5.3	3.6

TABLE II

COMPARISON OF THE RMS ERROR FOR AREA FOR DIFFERENT SPINE ARCHING.UNITS ARE MILLIMETRES, N=10.

Angle	L1	L2	L3	L4	L5	Average
0°	9.1	7	4.6	6.5	4.5	6.6
5°	10.7	5	5.7	12.9	11.4	9.6
10°	18.2	9.2	9.4	10.8	10.2	12

III. EXPERIMENTS AND RESULTS

Experiments were carried out on 10 volunteers following an informed consent and an error analysis was performed on each vertebra for each volunteer. Ultrasound images were obtained by an expert sonographer from L5-S1 up to L1. The sonographer identified the lumbar levels by freehand scanning of the vertebral laminae in a parasagittal plane that was within 10 mm of the midline plane. Identification of the vertebral levels by the sonographer was done by counting up from the sacrum or by counting down from the bottom rib. These measurements were taken by labeling the skin and will be referred to as "sonographer measurements" and considered as the gold standard. The error is defined as the difference between the system's displayed measurements and the sonographer's measurements on the skin. Several experiments were performed to determine the accuracy and robustness of image segmentation, augmented reality overlay and the inherent variability in the sonographer's measurements. The experiments performed are: (a) variance of sonographer measurements, (b) overall system accuracy, and (c) sensitivity of the system to changes in spine arching.

To determine the vairance of the sonographer measurements, the sonographer was asked to label vertebral levels on the same volunteer 10 times. The sonographer performed each trial independently from all previous trials, so the sonographer could not see the results of previous trials to avoid any biased results. The variance was 8.8 mm which is primarily due to different parasagittal planes used by the sonographer in each scanning session. This variance should not be considered as an error because it reflects the uncertainty of deciding which landmark to use for identifying a vertebrae.

The second experiment was performed on 10 volunteers in a sitting position without arching. The error for each vertebra was measured and the overall RMS error was also calculated from the individual sonographer's measurements. The results of this experiment are shown in Table I.

In the procedure of spinal needle insertion, the patient is typically asked to arch forward to increase spine arching. If a different amount of arching is present between the ultrasound scan and needle site selection, then additional errors will be produced because the patient's marker cannot measure the effect of arching. Therefore, a third experiment was performed to test the sensitivity of the system to changes in forward arching. In this experiment, the aim is to determine the effect of changes in the spine arching on the overall system accuracy. Here, after acquiring a sequence of ultrasound images in the resting position and augmenting the volunteers back with the detected lumbar levels, the subject was asked to bend forward until the screw angle, which was calculated as in [16], of the marker with respect to the resting position was changed by 5° and then 10°. Table II shows the error of the system against the sonographer's measurement in detecting the lumbar level for each bending angle.

IV. DISCUSSION AND CONCLUSION

In this paper, we presented AREA, a system developed to facilitate the guidance of epidural anaesthesia. The results show that using Micron Tracker with a simple setup can result in an acceptable level of accuracy for the correct identification of lumbar levels and augmenting lines on a patient's back. For epidurals, the overall accuracy requirements are specific to the first of the three stages of the procedure: (1) identification of the vertebrae level, (2) selection of the puncture site and needle angle, and (3) estimation of needle depth. The obtained system accuracy of 6.6 mm is equal to only 22% of average interspinous gap. Moreover, the standard deviation of error comparing AREA to sonographer measurements, as shown in Table I, was less than the interspinous gap, which is on average 31 mm. This error does not have significant effect on the subsequent measurement of the depth of insertion because of the small-angle geometry. In fact, it has been reported that for errors as high as 9.4 mm puncture site misplacement, only a 2% error in depth estimation will occur [12]. This is insignificant given the use of loss-of-resistance in epidural anaesthesia for final determination of the correct depth. Comparing the results obtained in this experiment with the previous method [8], the method in this paper has a higher accuracy 6.6 mm compared to 11.8 mm. It should be noted that such comparisons should be made with caution given a different set of subjects.

Another important source of error is the patient's motion. In our experiments, given a limited patient's motion up to 10°, the maximum error observed in detecting the lumbar level was 12 mm on average, which is still less than half of the interspinous gap. Given that the patient's marker was placed close to L3, the error was highest for the vertebrae farthest away, i.e. L1 and L5. These errors are less important because L1 and L5 are farthest from the typical injection site that is generally close to L3 (L3-L4 or L4-L5).

We have designed AREA as a reconfigurable platform that easily fits within the established clinical workflow for epidural anesthesia. It is anticipated that AREA could be used immediately prior to performing the needle insertion procedure, where the panorama scan takes approximately 2 minutes, the processing is nearly instantaneous, and the subsequent needle insertion follows the guidance provided by AREA on the monitor. In this way, only 2 additional minutes are added to the workflow. Moreover, the only computer interaction is via the foot pedal, and the ultrasound probe is covered with a sterile drape, so AREA can be used by a single anesthesiologist without disrupting the sterile field or need for an assistant. Future work will involve augmenting the image overlay with a statistical shape model of the lumbar spine registered to the panorama ultrasound image [13]. While this registration may not be highly accurate, it will provide the clinician with a three-dimensional context of the underlying anatomy and facilitates the interpretation of real-time ultrasound images. The next expected clinical applications for the system are for epidural, and then for facet joints injection for pain management, a procedure that is currently performed under X-ray fluoroscopy or Computed Tomography (CT).

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