DESIGN OF A PRECISION GUIDANCE SYSTEM FOR EPIDURAL ANESTHESIA

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ABSTRACT
In this paper, we propose an ultrasound image guided system to help the anaesthetist to perform epidural needle placement. Ultrasound images are utilized to find a best insertion point and insertion angle for the epidural needle. While various methods have been proposed to identify the epidural space, and to ensure that the epidural needle will be placed at the exact place without puncturing the dura mater. The proposed system is designed to greatly facilitate the anaesthetists work, improve the successful rate of epidural needle placement, as well as improve the efficiency of epidural anaesthesia.

KEY WORDS
Epidural Anesthesia, Ultrasound Imaging, Loss of Resistance, Automatic Needle Placement.

1 Introduction
Epidural anesthesia is widely used on women at the point of delivery of babies, in order to alleviate the labor pain and at the same time maintain their motor ability. During the epidural anesthesia, an epidural needle, usually a Tuohy needle with a hole in the center, is inserted to the epidural space, a narrow space surrounding the spinal column. After the successful placement of the epidural needle, a catheter will be inserted into the epidural space via the hole of the needle, which is used for the infusion of medicine.

Currently, the failure rate for epidural anesthesia is among 6-25% [1], which depends mostly on the experience and skill of the anesthetists. The main challenge in the epidural anesthesia is to (1) insert the epidural needle along a proper path into the epidural space; and (2) place the needle among the epidural space without puncturing the dura mater, a layer protect the spine column, the failure of which will lead to heavy headache lasting for hours.

Palpation on surface anatomical feature and loss-of-resistance technique are the two skills mainly used during an epidural anesthesia. Anesthetists palpate on the back of the patient to find proper insertion point for the needle, which requires experience to allocate the exact site at the first try. Further more, if the patient is obese, which is often the case for pregnant women, or that the patient has abnormal spine structure, the difficulty to allocate the proper insertion site by palpation will also increase.

Otherwise than palpation to find the insertion site, another important skill used when conducting epidural anesthesia is the loss-of-resistance technique, which refers to the phenomenon when the needle tip punctures through the ligamentum flavum (a high density tissue outside of epidural space) and enters the epidural space, the pressure inside the syringe will drop dramatically. During the insertion process, the anesthetists apply an constant pressure on the syringe. When the epidural space is reached, the pressure will drop and anesthetists will feel a loss-of-resistance [2]. The anesthetist should well control the force and speed of the epidural needle to ensure that the needle could puncture through the ligamentum flavum but stay inside at the epidural space (3-10mm in width), not puncturing to the dura mater. The anesthetists use one hand to apply constant pressure on the syringe and the other hand to push the epidural needle forward. Therefore, it requires high skills to ensure a successful needle insertion.

Anesthetists conduct epidural anesthesia depending on their experience and 'feeling', a blind technique which is highly risky for young anesthetists. In order to facilitate the epidural anesthesia, medical imaging is introduced into the process. Among the commonly used medical imaging methods, since radiography based imaging method, like X-ray and tomography, is usually radioactive and not safe for pregnant women, while Magnetic resonance imaging (MRI) is excessively expensive and the strong magnetic field is incompatible with the metal epidural needle, ultrasound imaging reasonably becomes the most widely used image technique to assist epidural anesthesia. There are various research or reports that ultrasound image improves the successful rate of the needle placement [3][7]. For some cases where it is almost impossible to insert the needle to the epidural space with palpation even after several times trial, ultrasound image helps to find a proper path and so the anesthetists could insert the needle successfully [8][9].

Even though ultrasound image provides the anesthetists with valuable information about the anatomy structure of the patients spine, it takes plenty of time for marking features on the skin of the patient, which is later used to locate the epidural needle [14]. Additionally, due to the limitation of manual drawing, the precision
of marking based location shall be decreased. What’s more, the surface marking can only help the anesthetists to locate the insertion point, it still requires high skills for the anesthetists to place the epidural needle in the epidural space using the loss-of-resistance technique. It cannot help to prevent the occasional and accidental dura mater puncture.

In this paper, we propose an assistive system to facilitate the epidural anesthesia under the guidance of ultrasound imaging. The system is designed to function in an automatic or semi-automatic way, which can greatly help the anesthetists to conduct the epidural anesthesia. It is also expected that this system will increase the successful rate of needle placement as well as being more effective, shortening the time needed for epidural anesthesia. In the following sections, the proposed solutions and system configuration will be explained in details.

2 Anatomy Structure of Spine

Before going deeper into the solutions section, it is necessary to introduce the anatomy structure of spine, in order to identify the epidural space.

The spine consists of 33 vertebrae comprising 7 cervical, 12 thoracic, 5 lumbar and 5 sacral vertebrae. Those vertebrae house the epidural and the subarachnoid spaces [12]. The interspaces between L2-L3 and L3-L4 are mostly often used for epidural needle insertion, because they give the largest interspinous distances, which would greatly decrease the difficulty of needle placement compared with the interspaces in thoracic place or other lumbar interspinous places [12].

As shown in the Figure 1 below, epidural space lies between the dura mater and spinous processes, behind the ligamentum flavum while outside the dura mater. Ligamentum flavum is thickest in the midline (3-5mm at L2-L3) and also farthest from the dura mater in the midline (4-6mm at L2-L3) [13]. Therefore, if epidural needle is inserted along the midline, the risk of puncturing dura mater would be lowered.

The most ubiquitous material in the epidural space is fat. Therefore, when the needle tip passes through the ligamentum flavum, the pressure inside the syringe would drop dramatically, the so-called loss-of-resistance technique used to identify the epidural space.

3 Proposed Solutions

As discussed in the introduction part, key challenges of epidural anesthesia lie in the location of needle insertion point and identification of epidural space. Solutions for these two challenges would be discussed in this section.

3.1 Identification of Needle Entry Path

In order to guarantee a safe needle path into the epidural space, two parameters would be required: the needle insertion point and needle insertion angle. Ultrasound image, as a non-radiative and cheap medical imaging technique, could be used to obtain the anatomy structure of spinal bones and find a bone-free path into the epidural space. If the obtained position and angle data could be precisely followed by the anesthetists, it can almost ensure a successful epidural needle placement, provided that the loss-of-resistance technique could be implemented accurately.

When the ultrasound transducer is at different positions or different orientations, the image detected by the ultrasound transducer would be different. If the ultrasound transducer is placed above the spinous processes, the image view beneath the bone would be dark and no details would be revealed, since ultrasound signals cannot penetrate through bones. While if the ultrasound transducer is placed among the interspaces, where the ultrasound waves would encounter no bones in the path, the image view would be bright and the details beneath the skin would be clear. According to these basic differences, it is possible to judge whether a certain point is suitable for epidural needle insertion or not.

Two orientations are generally used for spine anatomy detection: the paramedian longitudinal approach and the transverse midline approach. In the paramedian longitudinal approach, the ultrasound transducer is positioned vertically, perpendicular to the long axis of the spine, as showed in Figure 2. The ‘saw’ feature on the image represents the articular processes; the ‘short line’ beneath the articular processes represents ligamentum flavum and dura mater [14].

For the transverse midline approach, the ultrasound transducer is positioned horizontally, perpendicular to the
long axis of the spine. When the transducer moves from one spinous process to another, the image view would change along with the position of the transducer. As indicated in the Figure 3 and Figure 4, the obtained ultrasound images have distinct features. In Figure 3, the ultrasound transducer is above a spinous process, the bone prevent the ultrasound wave from penetrating it, thus a triangular dark shadow appears. When the transducer is positioned in the interspinous section, as indicated in Figure 4, the ultrasound wave could reach till the vertebra body, showing details of the ligamentum flavum (usually appearing together with dura mater as a single layer in the ultrasound image, since they are too close to each other), articular process and transverse process.

Generally, in the manual method, both longitudinal and transverse approach are used to identify the needle insertion point. The longitudinal view provides the interspinous level (the valley of the 'saw'), while the transverse view provides the midline point (midline is rightly above the spinous process in the transverse view). The anesthetists mark the two lines on the back of the patients and the intersection of them is the needle insertion point.

However, theoretically, it is possible to identify the needle insertion point with transverse midline approach alone. The transverse approach would reveal enough landmarks for insertion of epidural needles [10]. When the ultrasound transducer is above the interspinous process, as showed in Figure 3, the midpoint line could be identified; when the ultrasound image view reveals more details of the ligamentum flavum, as indicated in figure 4, then the needle insertion level could be identified. In the transverse approach, the ultrasound probe is initially placed perpendicular to the skin, since this angle has higher possibility of obtaining optimum quality image and only minimum change of angle is required if the obtained image quality is not satisfactory[11].

Therefore, in our proposed solutions, the needle insertion point and angle are determined by moving the ultrasound transducer along the spine with transverse midline approach. When the ligamentum flavum and other details beneath the skin is revealed, the system recorded the position and angle of the ultrasound transducer. In the second stage, the needle follows the same path as identified by the transducer. Then the needle could be successfully inserted without being impeded by the spinous processes.

### 3.2 Identification of Epidural Space

As discussed in the introduction section, the epidural space is mainly identified by the loss-of-resistance technique. When the needle tip punctures through the ligamentum flavum and reaches the epidural space, the pressure inside the syringe would drop and liquid or air inside the piston would be easily released. However, the main challenge in the implementation of loss of resistance technique lies in that, the anesthetists have to use one hand to apply constant pressure on the syringe, while use another hand to push the epidural needle forward. In this process, it requires high skills to control the epidural needle puncturing the ligamentum flavum and stops at the epidural space, without puncturing the dura mater.

Otherwise than the loss of resistance technique, several other methods can also be used independently or
complementary to identify the reach of epidural space. Along with the loss of pressure value, the force applied on the needle would also drop dramatically [15], as showed in Figure 5. Therefore, other than the pressure drop, it is possible to identify the epidural space with the force drop. A force sensor could be mounted on the epidural needle wings to record the force data along with the insertion of needle. However, if the system totally depends on force alone to identify the epidural space, there might occur false identification, since force drop also appears when the epidural needle penetrate the skin.

Ultrasound image could also be served as a complementary method to locate the epidural space. Depth from skin to the epidural space could be obtained by the ultrasound image, which could be served as a reference during needle insertion. However, only ultrasound image cannot locate the epidural space with high successful rate. For one reason, the ligamentum flavum and dura mater, sometimes cannot be clearly differentiated by the ultrasound image and just appears as one layer. So the epidural space between those two tissue cannot be measured precisely. For another reason, when body tissue is under pressure of needle insertion, the depth would change, not exactly the depth as measured by ultrasound image.

In order to improve the successful rate of epidural space identification, those methods could be combined together to provide a valid identification. The force drop detected by force sensor and depth information provided by ultrasound image could be correlated. When the needle insertion depth approaches the ultrasound image provided depth, the needle insertion speed could be slowed down and when the force drop appears, it is almost sure to identify that the epidural space has been reached. Simultaneously, loss of resistance could also be applied to double check the arrival of needle tip to the epidural space. In this approach, the successful rate of epidural space identification could be improved greatly.

4 Proposed System Configuration

In the last section, general solution for the epidural needle placement has been discussed. In this section, a proposal for the realization and configuration of the system would be explained in details.

In order to realize the automatic epidural needle insertion, the system should fulfill at least three functions, comprising needle insertion path identification, automatic needle insertion and epidural space identification. In addition, It is also necessary that the system should be able to record the position and angle of ultrasound transducer, and to keep the needle advancing following the same path. Therefore, four subsystems are needed, corresponding to each function: the ultrasound transducer (medical image processing), the needle insertion device, the epidural identification pressure detection system and the multi-DOF platform.

4.1 Ultrasound Transducer & Medical Image Processing

Ultrasound transducer obtains the spine structure and provides the insertion position & angle in to the epidural space. As showed in Figure 2-4, when ultrasound transducer is placed among the interspinous places, details of ligamentum flavum and vertebra body would be revealed. Otherwise, it the transducer is above the spinous processed, the image would have a triangular shadow in the middle, no details would be disclosed. According to this difference, if
detailed feature of ligamentum flavum and vertebra body is showed in the image, we can define that the position and angle of the probe is proper for needle insertion, which would be recorded and used as the parameter for automatic needle insertion device.

However, the problem is, professionalized anesthetists might not be able to read the ultrasound image and tell the difference between each image view, which requires skills and years of training. Therefore, complementary illustrations should be provided to the anesthetists to help them read the ultrasound image. Further, this procedure could even be processed as a black box model to the doctor. When the ultrasound image reveals related features, the system would record this position and angle data automatically, without the intervene of anesthetists. However, in order to prevent possible misjudgment of the automatic system, the final image view shall be presented to the anesthetists, with proper illustrations to facilitate understanding.

### 4.2 Needle Insertion Device & Multi-DOF Platform

The multi-DOF platform is used to support the ultrasound transducer and needle insertion device. It can be either manual or automatic. When anesthetists move the probe and locate a proper insertion point, each active DOF of the platform would be fixed, thus the position and angle of insertion path is mechanically recorded. Then needle insertion device would be moved to the position & angle by compensation and then advances following the predefined path.

The needle insertion device, as showed in Figure 6, is actuated by a step motor with an external screw, which translate the rotatory motion of step motor into linear movement. Thus, the epidural needle is promoted to the epidural space. Furthermore, the force of pushing forward the epidural needle would be detected by force sensor. When detected force increases, indicating passing through dense tissues like ligamentum flavum, the speed of step motor would be slowed down, enabling safely puncturing. When epidural space is successfully identified, the motor could be stopped immediately, therefore, ensuring not to puncture the dura mater.

As discussed in the previous section, epidural space could be identified by various methods. In order to increase the successful rate of identification, several approaches could be combined together. The force sensor mounted on the needle insertion device would be correlated with the depth information provided by the ultrasound image. When needle insertion length approaches the depth data, if then the detected force drops, then it can be defined that epidural space has been reached. The loss of resistance would be used to double check the validity of the identification.

A separate device is designed to apply constant pressures on the syringe with a spring, as showed in Figure 7. Therefore, there is no need that anesthetists have to apply pressure with their hands. Before epidural space is reached, the constant pressure provided by the compressed spring cannot push the syringe forward, since the pressure inside the body is higher. While if the needle tip arrives at epidural space, the pressure inside the syringe would be higher than the pressure in the epidural space. Thus the liquid inside the syringe would be pressed out.

### 4.3 Epidural Identification Pressure System

The working procedure of the automatic system, in short, is finding a insertion point and then insertion the epidural needle. The ultrasound transducer and the needle insertion device is fixed on the multi-DOF platform, while the pressure system is connected to the epidural needle via a long soft tube. When proper insertion point is located by the ultrasound transducer, the needle insertion device would move to the exact point after compensation. When the needle tip reaches at the epidural space, compressed springs in the pressure system would be released, then the needle would be stopped from advancing. Thus a successful epidural needle placement is finished.

### 4.4 The Overall System

The whole system is the combination of the four subsystem, as showed in Figure 8. The ultrasound transducer and the needle insertion device is fixed on the multi-DOF platform, while the pressure system is connected to the epidural needle via a long soft tube. When proper insertion point is located by the ultrasound transducer, the needle insertion device would move to the exact point after compensation. When the needle tip reaches at the epidural space, compressed springs in the pressure system would be released, then the needle would be stopped from advancing. Thus a successful epidural needle placement is finished.

### 4.5 Proposed Working Procedure

The working procedure of the automatic system, in short, is finding a insertion point and then insertion the epidural needle. The ultrasound transducer is held with the transverse view and slowly moved along the spine. When the best quality image is revealed, which indicates the best insertion path, the system would send out a signal and
tell the anesthetists to stop moving and fixed the platform. Then after needle position compensation, the stepper motor would be activated and the needle would be advanced along the insertion path found by the ultrasound transducer. The stepper motor would be stopped immediately at the epidural space without puncturing the dura mater, once the loss-of-resistance/force is detected by the pressure system and force sensor. A detailed working procedure is showed in Figure 9.

5 Discussion

The most challenging part in this project is the analysis of ultrasound image. It requires years of experience for the doctors to understand the ultrasound image, which might be blur and with low resolution. If we are able to extract the key features from the obtained ultrasound image and then give illustrations, it would greatly facilitate the anesthetists’s work. Usually, since our focus is only the spine structure, it is possible to find a generalized feature for specific positions.

In the general practice, anesthetists use one hand to apply constant pressures on the syringe and use another hand to push the needle forward. It is highly possible that the dura mater would be punctured if the anesthetists failed to dexterously control the pushing force with one hand. We propose to use automatic needle advancing device to assist the anesthetists’s work. The device is actuated by step motor and can be stopped immediately if epidural space is reached, without puncturing the dura mater.

Since the assistive device is guided by ultrasound image, using various methods to identify the epidural space and able to stop precisely at the epidural space once it is identified, therefore, the needle insertion path and epidural space can both be identified in an parameterized approach, rather than the blind procedure which totally depends on experience. It is supposed that the system could improve the successful rate of the epidural anesthesia, release the pain suffer of labor delivering, and also improve the efficiency by shorting the processing time. Furthermore, the system can serve as an assistive tool to help the trainee anesthetists to gain experience while at the same time guarantee the successful rate of epidural anesthesia.

6 Conclusion

In order to facilitate the needle placement for epidural anesthesia, an automatic ultrasound image guided epidural needle insertion device is proposed. The system is composed of ultrasound transducer, needle insertion device, multi-DOF system and epidural space identification pressure system. With the assistance of this device, it is supposed that the epidural anesthetists’ work would be greatly facilitated.
References


