Eyes on the needle: Identification and confirmation of the epidural space

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A B S T R A C T

Epidural catheters are used to provide effective intraoperative and postoperative analgesia. Standard epidural catheterization techniques rely on palpation of surface anatomy and the experience of the anesthesiologist. Failure to correctly place an epidural catheter can lead to inadequate analgesia and serious complications, such as dural puncture headache. Exciting new devices and techniques are being developed for identification of the epidural space and confirmation of catheter entry. This article reviews and describes the recent research findings. The devices and techniques are categorized into three sections: devices that modify the loss of resistance technique; visual confirmation using the epidural needle; and confirmation of placement of the epidural catheter.

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1. Introduction

Epidural catheters are used to provide effective intraoperative and postoperative analgesia. Standard epidural catheterization techniques, namely the loss of resistance (LOR) and saline drop methods, rely on palpation of surface anatomy and the experience of the anesthesiologist. Incorrect placement of the epidural catheter is reported to occur in 12%–40% of cases.1–3 The success of the procedure depends on the experience of the operator, patient positioning, body habitus, and spinal anatomy.4,5 Accurate placement of an epidural catheter is one of the more difficult skills that need to be mastered by anesthesiology residents, and approximately 60–90 placements may be needed to reach a technical plateau.6 Further, even if the correct needle trajectory is used to approach the epidural space, the risk of failed catheter placement is still high. The consequences of this failure include false-positive identification of the epidural space, difficulty in advancing the epidural catheter, inadequate epidural analgesia, and migration or dislodgement of the catheter.

Traditionally, confirmation of needle entry into the epidural space has required an experienced operator, LOR to air or saline, and administration of 2–3 mL test doses of xylocaine 1%–2% to confirm that the epidural catheter is correctly placed. Many techniques have been developed to provide an “eye on the needle” that can identify structures as the needle advances through the tissues. This review describes the techniques available for identification of the epidural space and confirmation of placement of the epidural catheter, as well as their efficacy. Their characteristics are summarized in Table 2. Advantages and disadvantages are summarized in Table 2.

2. Loss of resistance to air or saline and modification devices

Use of the LOR technique to identify the epidural space was first described by Sicard and Forestier in 1921. The epidural space is under lower pressure than that of the surrounding tissues, thereby allowing LOR to air or saline.7 The LOR technique requires the least additional equipment and is the most commonly performed method to date.

LOR is a subjective technique that requires experience in interpreting (“feeling”) a change in pressure by hand and the failure rate may be up to 5%–15% in inexperienced hands.8 The long epidural needle can be easily blocked by a blood clot or tissue, and so cannot indicate LOR reliably. The LOR technique using air is associated with complications, including headache, nerve damage, and interference with spread of the drug, leading to inadequate analgesia. Use of saline avoids these complications but does not provide the same “feel” as air. Several alternative techniques, mostly involving adapted or automated mechanical or pneumatic feedback, to detect a change in resistance or pressure have been proposed.
Table 1
Comparison of modalities investigated for identification of the epidural space.

<table>
<thead>
<tr>
<th>Identify inadvertent intrathecal and intravascular catheter placement</th>
<th>Differential visualization of soft tissue (artery, vein, nerve, epidural space)</th>
<th>Commercialized Human study</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOR modification devices</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Membrane in syringe</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Epidural balloon and Epidrum</td>
<td>−</td>
<td>+</td>
</tr>
<tr>
<td>Episure</td>
<td>−</td>
<td>+</td>
</tr>
<tr>
<td>EpiFaith</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Acoustic puncture assist device</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Fiber Bragg sensor</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Visual confirmation using the epidural needle</td>
<td>Optical spectroscopy</td>
<td>+</td>
</tr>
<tr>
<td>Ultrasound</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Optical coherence tomography</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Confirmation of epidural catheter placement</td>
<td>Electrophysiological stimulation</td>
<td>+</td>
</tr>
<tr>
<td>Pulsatile pressure waveform</td>
<td>+</td>
<td>−</td>
</tr>
<tr>
<td>Epidurography</td>
<td>+</td>
<td>−</td>
</tr>
</tbody>
</table>

LOS, loss of resistance.

Table 2
Advantages and disadvantages of epidural space identification techniques.

<table>
<thead>
<tr>
<th>Loss of resistance to air or saline and modification devices</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>May be beneficial for beginners and can be used for demonstration purposes</td>
<td>Additional equipment required</td>
<td>Not proven to be superior to the loss of resistance technique performed by an experienced operator</td>
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</table>

Visual confirmation using the epidural needle

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real-time imaging of the ligamentum flavum, epidural space, and dura</td>
<td>Poor penetration depth</td>
</tr>
<tr>
<td>Data are difficult to interpret, and may require assistance of artificial intelligence</td>
<td>No human studies performed to date</td>
</tr>
</tbody>
</table>
| Confirmation of epidural catheter placement

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Can be performed with existing equipment by simply connecting a nerve stimulator or pressure transducer to the catheter</td>
<td>Can be performed in infants or patients who cannot communicate verbally</td>
</tr>
<tr>
<td>Can be performed in infants or patients who cannot communicate verbally</td>
<td>Technically difficult to perform in the peroperative setting</td>
</tr>
<tr>
<td>Confirmation after catheter placement in combination with loss of resistance technique</td>
<td></td>
</tr>
</tbody>
</table>

2.2. Epidrum and ProDural epidural balloons

Macintosh proposed the use of epidural balloons in 1950. An epidural balloon consists of a small inflated balloon attached to an epidural needle. The negative pressure resulting from the tip of the needle entering the epidural space causes the balloon to collapse, thereby providing a visual indicator of LOR. The ProDural and Epidrum are similar in concept and both use a small drum with a diaphragm. Use of a visual indicator of LOR allows a shorter procedure time and fewer attempts when compared with the traditional LOR technique.15,11 However, use of these devices does not improve the success rate15 or avoid the complications of injection of air into the epidural space.

2.3. Episure AutoDetect syringe

Mechanical devices such as the Episure AutoDetect syringe provide visual confirmation of LOR. This syringe includes an internal compression spring that applies constant pressure on the plunger and automatically depresses when the needle enters the epidural space.13 Saline is used because of the high false-positive rate with air. This method allows visual confirmation of the epidural space and requires two-handed operation when advancing the needle. This technique also has a rapid learning curve and is highly successful in achieving analgesia.14 In a pilot study that included predominantly anesthesiology residents, the puncture and success rates were higher than those achieved using a conventional syringe.15 but not in a similar study conducted in anesthesiologists who were experienced providers of epidural analgesia.14

2.4. Acoustic puncture assist device

In 2004, Lechner et al described a technique whereby a pressure change is amplified and transformed into an acoustic signal that indicates the epidural space.16,17 Using this method, a saline flush needle is attached to an infusion pump, along with an acoustic amplifier and a visual pressure display. As the needle passes from the ligamentum flavum (a high pressure zone) to the epidural space (a low pressure zone), the acoustic system lowers its beep tone, alerting the anesthesiologist to the fact that the epidural space has been entered. This system can differentiate between the epidural space and a false cavity because of differences in the pressure change between the two structures, thereby decreasing the false-positive rate.17 Lechner et al achieved high success rates for both thoracic and lumbar epidural procedures using this technique. However, the set-up of the system was not suitable for routine daily practice, so it was never commercialized.

2.5. EpiFaith syringe

This syringe is equipped with a mechanical device that ensures the needle will come to an abrupt halt when it reaches the epidural space, where there is a pressure change. This strategy can help to reduce the risk of accidental dural puncture. The EpiFaith syringe is mechanically driven, consistent with current practice, and is compatible with other accessories presently in use. However, there is sparse information in the literature regarding its efficacy and sensitivity.

2.6. Fiber Bragg sensors

A fiber Bragg sensor (FBS) is a segment of optical fiber characterized by periodic modulation of the refraction index along the axis of the fiber core. The grating acts as a band filter to allow
certain (Bragg) wavelengths of light to be reflected. The Bragg wavelength is proportional to the net effective refractive index of the fiber medium and can be influenced by heat, bending of the fiber, or a change in pressure. Carotenuto et al proposed a probe consisting of an FBG with a special coating that works as a sensorized stylus, which discriminates between different types of tissue and thus provides continuous and real-time measurements of the pressure encountered by the tip of the needle as it advances.\textsuperscript{18,19} The epidural space is identified when abrupt relaxation of the fiber is detected as it passes from a thin and very hard tissue (ligament flavum) to a soft region (epidural space). The probe contains an FBG written in a single mode optical fiber (125 μm diameter) working as a single-ended strain sensor. Using an epidural training phantom, the authors demonstrated that the FBG could detect abrupt pressure changes effectively. In vivo studies of this technique are presently under way.

3. Visual confirmation using the epidural needle

The epidural needle passes through several tissue layers, including the skin, subcutaneous fat, supraspinous and inter-spinous ligaments, and the ligamentum flavum, before reaching the epidural space. Conventional “blind” attempts can result in failure of epidural placement and serious complications, including peripheral nerve damage and dural puncture. Several methods have been proposed to guide needle investigation and have yielded promising results.

3.1. Optical spectroscopy

Optical spectroscopy is a measurement of tissue optical absorption using visible and near-infrared light that can differentiate tissues. The rationale for this method is based on different tissues having different hemoglobin, lipid, and water content. Desjardins et al incorporated spectroscopy fibers into the epidural needle and used light in the 500–1000 nm range to obtain tissue spectra in a swine cadaver model.\textsuperscript{20} The image depth was approximately 1.2 mm for incident light at 500 nm. Ting et al independently developed a similar technique in 2010 using 532 nm and 650 nm light reflection in an in vivo swine model that showed specific reflective optical characteristics in the ligamentum flavum and epidural space.\textsuperscript{21} Optical fibers were inserted into the epidural needle and connected to a fiber optic spectrometer. This method has been reported to have a sensitivity of 80%–85% and a 95% success rate.\textsuperscript{22} A portable model with an alarm system was developed for ease of use.\textsuperscript{23} Interpretation of data can be difficult for those unfamiliar with the display, so Lin et al developed an algorithm using artificial intelligence that could interpret incoming quantitative data from the optical fibers and categorize them as likely representing the ligamentum flavum or epidural space, or as indeterminate.\textsuperscript{24} A success rate of 97.9% could be achieved using this method.\textsuperscript{22} Further, Rathmell et al reported that use of broad-spectrum in vivo light resection in an epidural training phantom may be overcome by using Raman spectroscopy, which is better predictive accuracy for identifying tissues and differentiating them from the epidural space.\textsuperscript{25} Further, the Raman spectrum for each tissue was found to be unique and could be identified based on the relative amounts of albumin, actin, collagen, triolein, and phosphatidylcholine, and was not influenced by tissue density. However, the use of Raman spectroscopy in vivo needs to be explored further.

Thus far, spectroscopy has been the most accurate and learnable method for identifying the epidural space. However, no study in humans has been reported.

3.2. Ultrasound

Ultrasound can be utilized in two ways. Given its good penetration depth, surface ultrasound can be performed with either a linear probe in lean patients or a curved probe in obese patients. Ultrasound provides essential and reliable information about the surrounding structures. Both the vertebral space and the dura can be identified. Needle guidance can be performed in real-time as a two-person technique with a high success rate.\textsuperscript{26} However, placement of the epidural catheter cannot be visualized and a one-person technique may be difficult.

Chiang et al incorporated a 40 MHz ultrasound transducer fiber (–6 dB fractional bandwidth 50%) into an 18-gauge needle to obtain an A-mode image display. The amplitude of the ultrasound signal was displayed on the y axis and the time needed for ultrasound return was displayed on the x axis.\textsuperscript{27} The axial resolution was 0.15 mm and the penetration was 10 mm. By displaying the A-mode scan on a two-dimensional depth-reconstructed scan image, the ligamentum flavum, epidural space, and entry of the needle could be visualized.\textsuperscript{28} The ligamentum flavum was identified on 83.3% of insertions and the dura matter on 100% of insertions. Ameri et al further proposed that the efficacy of this method could be improved by incorporating A-mode imaging with two-dimensional B-mode imaging, which displays the brightness of the ultrasound signal.\textsuperscript{29} A 2 cm depth could be achieved by the B-mode needle probe, which improved the accuracy and safety of epidural catheter placement in animal models. However, human studies are lacking. Other sensing modalities, such as pulse-echo ultrasound,\textsuperscript{30} are being explored.

3.3. Optical coherence tomography

Optical coherence tomography (OCT) is an optical imaging modality similar in physical principle to ultrasound except that it uses infrared light. Using OCT, it is possible to obtain high-resolution, cross-sectional, subsurface tomographic images of tissue microstructure. Tang et al developed a small-diameter (0.5 mm) forward imaging OCT system together with high-contrast Doppler flow imaging in real time.\textsuperscript{31} The frequency domain OCT system utilizes a wavelength-swept laser that is centered at 1310 nm with a bandwidth of 100 nm. Both the lateral and axial resolutions are around 13 μm. This system can visualize arteries, veins, and differential structures layer by layer.\textsuperscript{32}

Kuo et al also described an in-needle swept-source OCT system with high sensitivity and high specificity.\textsuperscript{33} A two-dimensional OCT image was acquired by circumferential scanning using an optical probe placed in an epidural needle with a rotational motor, which demonstrates real-time side view images as the needle progresses into the epidural space. The axial resolution is about 15 μm in tissue and the imaging depth is approximately 2 mm. Instead of forward imaging, they proposed that a side-looking fiber probe could better differentiate the tissue layers. With the OCT probe in the epidural space, a whole circular image within the epidural channel was obtained in post-processing. The technological advance of increasing the imaging depth from 2 mm to 7 mm incremented use of OCT further. In 2016, Ding et al used a polarization-sensitive OCT system to differentiate tissue characteristics in real time.\textsuperscript{34} However, unlike the study by Kuo et al, their experiment was performed using a dissected pig spine specimen in which the different tissue...
layers were identified and separated first, and the OCT image was obtained in open air. Further in-needle imaging is needed before polarization-sensitive OCT can be applied for needle guidance. The fiber-in-needle devices allow single-person operation and can identify intravascular and intrathecal entry, but inexperienced readers may find the images difficult to interpret. Quantitative imaging parameters are needed for better classification of tissue types.

4. Confirmation of epidural catheter placement

An ideal confirmation test should be reliable and allow for adjustments at the time of insertion of the epidural catheter. Several methods have been proposed for confirmation of epidural catheter placement.

4.1. Electrophysiological stimulation

In 1998, Tsui et al proposed a nerve stimulation technique using a current intensity of 1–10 mA.39 A nerve stimulator was connected to an existing epidural catheter via an electrophysiographic adapter and flushed with normal saline. The anode terminal of the stimulator was connected to an electrode placed over the deltoid muscle. Nerve stimulation was performed using a pulse width of 200 ms at a frequency of 1 Hz. A motor or sensory response indicates that the catheter tip has located the epidural space. The catheter may be in close proximity to the nerve root, in the subarachnoid space40 or in the subdural space41 if stimulation occurs at <1 mA. The sensitivity of this technique has been reported to be 80%–100%.42,43 This method can also be used to estimate the vertebral location of the catheter tip when a catheter is advanced for a long length along the epidural space, such as when an epidural catheter is placed caudally in an infant.44

4.2. Pulsatile pressure waveform

The epidural space has a pulsatile pressure that is synchronous with the heartbeat, and is known as the epidural pressure waveform. Measurement of pulsatile pressure waveforms was proposed as early as 1932, but was not taken up because of the difficulties in measuring and demonstrating these waveforms. In 2001, Ghia et al recorded epidural waveforms by connecting the epidural catheter to a pressure transducer flushed with saline and reported the feasibility of using these waveforms to confirm entry into the epidural space.45 In 2006, Lennox et al used this technique to confirm placement of the epidural catheter in the epidural space after conventional placement with LOR. They demonstrated a high sensitivity of 97.5%.46 This procedure can be performed using simple devices (pressure transducers) in the operating theater and may be helpful for confirming the position of the catheter in the perioperative setting when an epidural catheter is inadequate.

4.3. Epidurography

Confirmation of correct placement of the catheter in the epidural space is often performed by fluoroscopic-guided injection of contrast medium during pain procedures. Contrast dye is injected to demonstrate typical epidural spread under fluoroscopy. However, because of lack of equipment and concerns about the hazards of radiation, this technique is rarely used in the perioperative setting. This method may be useful if abdominal or thoracic X-rays are routinely obtained postoperatively for guidance before manipulating an inadequately functioning catheter.47

5. Conclusions

Newer methods for confirmation of entry into the epidural space should have high sensitivity and specificity. They should also be easy to learn and perform, preferably by one person. Exciting new techniques are being developed, but most are still in the experimental stages. Needle devices and techniques do not reduce the number of attempts required, enable identification of landmarks, or provide a guide for the trajectory path, and must be combined with surface ultrasound to increase their success rate. Identification algorithms could improve our ability to differentiate the epidural space. With these new developments, placement of epidural catheters could soon be accomplished by all anesthesiologists easily and safely.

Conflicts of interest

None.

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