Discriminant analysis for anaesthetic decision-making: an intelligent recognition system for epidural needle insertion


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Editor’s key points
- Epidural catheter misplacement can cause complications.
- Fibreoptic technology with discriminant analysis was used to determine epidural catheter placement.
- The method was as good as an experienced doctor.
- It would be even better with an ‘uncertain’ category.
- This technique may be able to reduce incorrect epidural placement.

Background. Incorrect placement of epidural catheters causes medical complications. We used linear discriminant analysis (LDA) to develop an intelligent recognition system (i-RS) in order to guide epidural placement and reduce physician error.

Methods. We analysed real-time dual-wavelength fibreoptic data recorded from the end of an epidural needle in a live porcine model. Two categories of tissue layers were necessary for correct placement of catheter: epidural space and ligamentum flavum. The data were tested using linear, quadratic and logistic parametric analysis to identify which method could distinguish the two anatomical structures.

Results. LDA was the best fit for our model. There was ≈80% sensitivity and specificity for correct anatomical identification. Error rates based on cross-validation were 17.0% for the epidural space and 18.6% for ligamentum flavum. Error rates were greater with the 532 nm compared with 650 nm wavelength.

Conclusions. The sensitivity and specificity of LDA for identifying the correct anatomical structure was similar to a physician who is an expert in epidural placement. Overall performance of an i-RS could be improved by expanding the database for decision-making and adding a category of uncertainty. This would reduce complications caused by incorrect epidural placement.

Keywords: anaesthetic techniques, epidural; measurement techniques, fibreoptic; model, pig; statistics

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Epidural anaesthesia is one type of neuraxial block. It is an effective way to control pain associated with surgery, labour and delivery, and chronic pain syndromes. The accuracy of catheter placement determines the effectiveness of epidural pain relief. Epidural catheters are inserted by passing a hollow needle through the tissues that surround the spinal cord. Subtle changes in the density of the tissues are interpreted by compressing a hollow using the plunger of a syringe attached to the needle. The most common complication of epidural anaesthesia is the failure to control pain because of incorrect placement.

Competency requires an average of 60–90 epidural placements. We recently reported the findings of a study using fibreoptic-assisted epidural placement. We showed that epidural catheters could be correctly placed with this technique.

In this study, we used discriminant analysis to interpret the fibreoptic information in order to build a real-time decision-support system for epidural placement. Discriminant analysis is a statistical method to develop a decision rule (discriminant function) that allocates an observation into defined classes by input variables. With this decision rule, our system can identify different tissues during epidural procedure layer by layer while receiving real-time two-wavelength optical signals from the epidural stylet.

Methods
Fibreoptic epidural insertion
This study was approved by the Institutional Animal Care and Use Committee of Taipei Veterans General Hospital. The experiments were performed in four Duroc and Landrace Chinese native pigs with an average weight of 20 kg. General anaesthesia was induced with tiletamine–zolazepam (5 mg kg⁻¹) i.m. After tracheal tube insertion, anaesthesia was then maintained with an i.v. infusion of...
pentobarbital sodium (15 mg h\(^{-1}\) kg\(^{-1}\)) till the duration of the experiments.

Study animals were then placed in the left lateral recumbent position for insertion of an epidural catheter. Epidural catheterization was performed with a 17-gauge insulated Touhy needle (Arrow, Teleflex Incorporated, Limerick, PA, USA) containing a fibreoptic stylet. In brief, a fibreoptic stylet was inserted into a standard hollow epidural needle. The optical needle was used to pierce the skin and then it was slowly pushed through the tissues with a trajectory aimed at the spinal cord of anaesthetized pigs. The optical signals were used to identify tissue planes and the epidural space.

Once the physician identified the epidural space, the fibreoptic stylet was removed and a catheter was threaded through the hollow needle. The position of the catheter in the epidural space was confirmed using ultrasound images and by injecting contrast medium into the catheter. The contrast medium was viewed by X-ray to determine if the catheter was within the boundaries of the epidural space. The animals were humanely euthanized after the procedure.

The fibreoptic stylet delivered laser light at wavelengths of 650 and 532 nm and received reflected light signals from the tissue layers and the epidural space. The reflected signals were displayed on a LCD oscilloscope with a fast analogue-to-digital converter (GW Instek, Hsinchu City, Taiwan; model GDS2104, 100 MHz, 4ch). The analogue information was interpreted by the physician placing the epidural. Both the 650 and 532 nm wavelengths were used to distinguish between the epidural space and ligamentum flavum.

Statistical modelling and discriminant analysis

We used parametric methods to analyse the data from two classes of observations of optical signals from the ligamentum flavum and the epidural space. During epidural placement, reflected light signals from each of the two anatomical structures were converted to digital information by a fast analogue-to-digital converter on the oscilloscope and automatically entered into a database. The digital signals were used for discriminant analysis. All parametric data are presented as mean (SD).

Data derived from the reflective signals were normalized by logarithmic transformation. We tested two classifiers for the discriminant analysis; linear and quadratic. We tested both methods as there were no data to indicate whether the pooled within-group covariance was identical or unequal. A test of homogeneity using Bartlett’s modification of the likelihood-ratio test showed that linear discriminant analysis (LDA) with pooled variance–covariance matrix was a better fit for our analysis.

Logistic discrimination was also tested against LDA. Assuming that prior probabilities of identifying two tissues are known and equal, we applied Bayes’ theorem as a classification procedure for all three discriminant methods tested and estimated the posterior probabilities of each observation. We also used backward selection in choosing variables of discriminant analysis. The performance of discriminant analyses was evaluated by estimation of the error rate (possibilities of misclassification). To reduce bias, we used leave-one-out cross-validation to verify our results. All statistical analyses were performed with SAS software (V9.2; SAS Institute Inc., Cary, NC, USA). A diagram of intelligent recognition system (i-RS) is shown in Figure 1.

Results

There were 90 pairs of reflective signals, where 43 pairs came from ligamentum flavum and 47 pairs came from the epidural space. Each pair of signals was emitted from the 650 and 532 nm wavelengths used in our study. Table 1 shows the data distribution. The standard deviations between the two classes of observations were similar, and the homogeneity test confirmed this finding with a value of \( P=0.113 \). A comparison of discriminant techniques (LDA and logistic discrimination) showed that LDA had a higher rate of correct identifications than logistic discrimination (82.2% vs 81.1%). LDA also had better sensitivity and specificity. This was particularly evident for the ligamentum flavum compared with epidural space (Table 2).

We therefore chose LDA to analyse our optical data in order to construct a system that uses pattern recognition to assist the physician in epidural placement. The classified observations are presented in Table 3. To reduce the bias of estimation classification error, we used leave-one-out cross-validation. This method achieves a nearly unbiased estimate.
upon clinician experience and technique. The amount of compression used to detect the epidural space is operator-dependent and difficult to quantify. Failure to obtain reliable observations allowed us to develop an i-RS for guiding epidural placement.

In this study, we built a theoretic i-RS using LDA of optical signals emitted during epidural catheter insertion. We collected data derived from a two-wavelength fibreoptic light source (536 and 650 nm laser) that provide real-time information locating the position of an epidural needle. The data naturally fell into two distinct classes of anatomical observations. Systematic testing of parametric methods showed that LDA was the best fit to discriminate between the epidural space and ligamentum flavum in our model. The LDA performed as well as physician interpretation of the optical signals in our previous study. This suggests that an i-RS using LDA for tissue recognition may be highly effective in decision-making during epidural placement.

The most common method to identify the epidural space uses the subjective interpretation of how the plunger of a syringe feels when air or fluid in the barrel is manually compressed while passing through the patient’s tissues. Interpretation of the tactile information is highly dependent upon clinician experience and technique. The amount of compression used to detect the epidural space is operator-dependent and difficult to quantify. Failure to obtain reliable data from the compression technique precludes the collection of objective data for statistical analysis. Real-time ultrasound had been used to guide the direction of epidural space, but not the depth of it. In order to solve this technical difficulty and obtain reliable observations, we developed a fibreoptic system that used reflected light signals from the anatomical structures that the needle traverses.

The technical steps required for fibreoptic-guided epidural catheterization are the same as the compression technique, except that there is a fibreoptic stylet inside the needle.

In our prior optical study, we found that accurate epidural placement was possible if either the ligamentum flavum or epidural space could be identified. Anatomically, the ligamentum flavum lies directly over the epidural space. The average thickness of the ligamentum flavum is only 5–6 mm and the width of the epidural space is ~5 mm in the lumbar area. The optical characteristics of the ligamentum flavum and epidural space using a 650 nm wavelength in our previous study were significantly different. These observations were not affected by the site of placement along the length of the spine. A linear mixed model analysis of our data showed no significant difference (P=0.9 for 650 nm and P=0.35 for 532 nm) in the optical properties of the ligamentum flavum or epidural space at different levels of the spine. The consistency within each of the two sets of observations allowed us to develop an i-RS for guiding epidural placement.

We used parametric methods where the optical data were segregated into two classes of observations (either ligamentum flavum or epidural space). Dimensionality reduction was performed using discriminant analysis of the electronic signals collected from fibreoptic-guided epidural placement in a living porcine model. There are only two possible decisions, each based upon the certainty of class identification. If the ligamentum flavum is identified, the needle is inserted deeper and if the epidural space is identified, the optical stylet is removed and the catheter inserted.

We used the data obtained from two optical wavelengths (532 and 650 nm reflective signals) as linear classifiers to segregate the data. The numerical optical values were analysed using the categorical variables of ligamentum flavum and epidural space as two classes of observations. We compared linear and quadratic discriminant analysis of our data and test of homogeneity showed that there were similarities between our groups (P=0.113). Therefore, LDA was a better fit for our model.

We also analysed the data using logistic discrimination. LDA is better suited to training sets with multivariate normal distribution. In contrast, under non-normality, logistic discrimination is preferred. We also used error rate

### Table 2: Performance of discriminant analyses with dual wavelength

<table>
<thead>
<tr>
<th>Discriminant analysis</th>
<th>Tissue layer</th>
<th>Sensitivity (%)</th>
<th>Specificity (%)</th>
<th>Error rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDA</td>
<td>Ligamentum flavum</td>
<td>81.4</td>
<td>83.0</td>
<td>18.6</td>
</tr>
<tr>
<td></td>
<td>Epidural space</td>
<td>83.0</td>
<td>81.4</td>
<td>17.0</td>
</tr>
<tr>
<td>Logistic discrimination</td>
<td>Ligamentum flavum</td>
<td>79.1</td>
<td>83.0</td>
<td>20.9</td>
</tr>
<tr>
<td></td>
<td>Epidural space</td>
<td>83.0</td>
<td>79.1</td>
<td>17.0</td>
</tr>
</tbody>
</table>

but a relatively large variance. Error rates of LDA based on cross-validation were 17.0% for epidural space and 18.6% for ligamentum flavum (Table 2).

Although no variables can be discarded after the backward variable selection procedure, the 650 nm wavelength provided the most information in discriminant analysis. We therefore tested a single variable (650 nm of reflective signal) for LDA and logistic discrimination. The performance of two discriminant analyses was similar. Estimated error rates for analyses of both ligamentum flavum and epidural space are 25.6% and 17.0%, respectively (Table 4).

### Table 3: Classification results of LDA with dual wavelength

<table>
<thead>
<tr>
<th>Original tissue layer</th>
<th>Classified tissue layer</th>
<th>Ligamentum flavum</th>
<th>Epidural space</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ligamentum flavum</td>
<td></td>
<td>35</td>
<td>8</td>
<td>43</td>
</tr>
<tr>
<td>Epidural space</td>
<td></td>
<td>8</td>
<td>39</td>
<td>47</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>43</td>
<td>47</td>
<td>90</td>
</tr>
</tbody>
</table>
estimation and rejection rate to assess discriminant performance. There was a lower ligamentum flavum identification rate using LDA compared with logistic discrimination. However, to avoid medical complications, the system must be modified to preferentially decrease epidural space error rate (or increase specificity of recognizing epidural space). Therefore, both discriminant analyses would perform equally well for this task.

The LDA performed as well as physician-based decision-making from our previous study. Sensitivity and specificity for identification of both the ligamentum flavum and epidural space were ~80%. However, it is possible that the error rate of optically guided epidural placement by physicians will be significantly greater than that observed in our previous study. All epidurals in our previous study were placed by one physician who was an expert in this field. In contrast, there is a much wider range of experience and expertise in the medical community. We anticipate that LDA would have been performed significantly better than physician-guided placement if the error rate of less-experienced physicians and trainees were included into our previous analysis.

In addition, we think that LDA performance could be improved with two modifications. The first is to improve the overall sensitivity and specificity of the LDA. This study was limited to only 90 observations from four study animals and it is likely that the addition of more data points will improve the overall performance. We also suggest that adding a category of uncertainty will also reduce our error rate, as sensitivity does not consider indeterminate observations or results. Inserting a catheter or advancing the epidural needle in this situation could result in serious medical complications.

And so, we suggest that it is reasonable to add a category of uncertainty in the medical decision-making process. This can be done by setting a minimum acceptable posterior probability ($d$) under Bayes' theorem as a safe threshold that will include a level of uncertainty. If the maximal posterior probability of each observation is less than $d$, it will be classed as 'doubt', that is a tradeoff question. Minimum acceptable posterior probability will decrease misclassification rate but increase the rejection rate (Table 5). This is acceptable in epidural placement because misclassification may result in complications. In contrast, if an observation is incorrectly rejected, there is no patient injury. The physician can redirect the needle and perform the procedure again.

We were able to further simplify our model by reducing the linear classifier to the 650 nm wavelength. The dual-wavelength analysis had more misclassification of the ligamentum flavum (18.6% vs 25.5%) but the same error rate of epidural space. This error rate could increase the number of medical complications. Data from the 532 nm wavelength failed to separate the ligamentum flavum from epidural space in our study. The peak absorption spectra of the deoxyhaemoglobin and oxyhaemoglobin of blood are near the 578 nm and 554 nm wavelengths, respectively. Light at a wavelength of 532 nm will be largely absorbed by the two haemoglobin subtypes and could contribute to erroneous readings.

In this study, we aimed to build a discriminant function (statistic model) from 90 pairs of optical data. The commonly used measure of a model's quality is predictive accuracy. The true error rate is usually estimated from all the available samples, which are split into training and testing sets. We understand that the training and the test sets should be of sufficient size and independent in character so that it can be used to generate a reliable estimate of the error rate. We had two important issues to consider when we chose a method to estimate the error rate (or misclassification).

There was concern that our model will not be very robust because the training set was small and consequently we may not be able to generalize the findings to other independent datasets. However, the confidence in the estimated error rate will be low because our test set was also small. We therefore chose a method to specifically deal with the limitations in our data. In our study, we used leave-one-out cross-validation to get an unbiased estimation of limited optic data points. This method is designed to test error rate within a single small dataset. It uses a single observation from the original sample as the validation data and the remaining observations are the training data. Thus, we used ($n - 1$) samples for training and evaluated the remaining sample. This is repeated so that each observation in the sample is

| Table 4 Performance of discriminant analyses based on uni-wavelength (reflective signal of 650 nm wavelength) |
|-------------------------------|-----------------|-----------------|-----------------|
| Discriminant analysis       | Tissue layer    | Sensitivity (%) | Specificity (%) | Error rate (%) |
| LDA                           | Ligamentum flavum | 74.4            | 83.0            | 25.6            |
|                               | Epidural space   | 83.0            | 74.4            | 17.0            |
| Logistic discrimination      | Ligamentum flavum | 74.4            | 83.0            | 25.6            |
|                               | Epidural space   | 83.0            | 74.4            | 17.0            |

| Table 5 Performance of LDA (532 and 650 nm) with different minimal acceptable posterior possibilities ($d$) |
|---------------------------------------------------------------|--------------|-----------------|-----------------|
| Minimum acceptable posterior probability ($d$) | Error rate (%) | Ligamentum flavum | Epidural space | Total rejection rate (%) |
| 0                             | 18.6         | 17.0            | 17.8            | 0               |
| 0.56                          | 16.3         | 17.0            | 15.6            | 3.3             |
| 0.58                          | 11.6         | 10.6            | 11.1            | 12.2            |
| 0.60                          | 9.3          | 8.5             | 8.9             | 17.8            |
used once as the validation data. This is a well-accepted approach but is used less often because it has large computational requirements. There are many examples of leave-one-out cross-validation in the medical field.29 30

There are several limitations to our study. First, optical observations in our animal model may differ from humans. The porcine model has been validated as a surrogate for human studies to evaluate the epidural needles in biomedical engineering.31 32 Although there are differences between porcine model and human anatomy, the basic anatomical features are similar. Further, there are additional changes in tissue hydration association with pregnancy that may further change the optical signals.33 Additional studies are therefore required in pregnant and non-pregnant patients to confirm our findings. Secondly, we used leave-one-out cross-validation to reduce bias of estimation error rate and external validation is required for this step. Thirdly, we did not include optical data from common medical complications including traversing the epidural space into the spinal cord. If the needle passes through the epidural space, fluid surrounding the spinal cord will flood into the sight of the needle and will significantly change the optical signals and thus the classification rule will also change under these conditions. This will require additional testing in our porcine model to assess the impact of this adverse event on data retrieval. Finally, our model does not address all the important challenges that are encountered in neuraxial anaesthesia. Our model is just the first step in exploring different possibilities of performing highly skilled technical procedures and the ultimate utility of our method will require extensive testing in humans. The method must be tested in conditions such as obesity, pregnancy and spinal deformities to determine what value it will ultimately have in clinical medicine.

In summary, this study showed that integration of computer-assisted recognition and fibreoptic technology can provide a real-time advisory support for anaesthetists when localizing epidural space. The system has the same sensitivity and specificity as physician interpretation of the optical data. However, redirection of the epidural needle when there is uncertainty should improve correct epidural placement compared with physician-based decision-making. We anticipate that LDA-based interpretation of optical data can provide a real-time advisory support for anaesthetists when there is uncertainty should improve correct epidural placement compared with physician-based decision-making. We anticipate that LDA-based interpretation of optical data when there is uncertainty should improve correct epidural placement compared with physician-based decision-making. 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