DESIGN AND DEVELOPMENT OF A VISUAL SYRINGE FOR EPIDURAL ENTRY

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ABSTRACT
Background: Inadvertent dural puncture is the most significant complication associated with epidural anaesthesia. These spinal taps can result in severe and prolonged headaches for the patient and, in rare cases, serious neurological complications. The current gold standard in epidural administration involves blindly passing a needle through the spinous processes of the vertebra until loss-of-resistance (LOR) is achieved on reaching the epidural space, resulting in a subtle and sudden pressure drop at the needle tip. The LOR technique relies exclusively on subjective haptic feedback on the syringe plunger and requires significant training until a reasonable proficiency is achieved. ProDural is a novel visual syringe for signalling needle entry into the epidural space. ProDural provides both visual and haptic feedback of probe entry into the epidural space by rapid and immediate collapse of an inflatable diaphragm whilst retaining haptic feedback.
Methods: ProDural was designed based on criteria established through end user surveys, ethnographic feedback and existing technology assessment. The resulting solution was evaluated through physical bench-top experiments and analytical modelling prior to a pre-clinical cadaver trial.
Conclusion: These initial trials indicate that ProDural may represent a promising approach to improving the accuracy of epidural needle placement and may reduce the steep learning curve associated with epidural administration.

KEY WORDS
Medical devices - Epidural administration - Visual pressure drop indicator.

1. Introduction

Epidural administration of local anaesthetic and/or opioids is performed for analgesia and anaesthesia in the perioperative or peripartum period or to provide analgesia before surgical procedures and labour. It is also commonly used as a therapeutic method for pain relief. The US Department of Health and Human services reported that 70.85% of births in the US in 2011involved epidural or spinal anaesthesia. This amounts to approximately 2.76m deliveries involving the provision of epidural/spinal anaesthesia during labour. Epidurals block the nerve impulses from certain spinal segments resulting in decreased local sensation. Although epidural anaesthesia has been part of anaesthetic practice since 1901, localisation of the epidural space remains technically difficult [1]. Epidural analgesia has been described as the gold standard of pain control [2]. The technique requires a clinician to blindly pass a needle through soft tissue and ligament between the caudally protruding spinous processes of the vertebrae. Confirmation of needle tip entry to the epidural space is most commonly achieved by the loss-of-resistance (LOR) technique; a sudden, yet subtle, pressure drop at the needle tip which is sensed at the syringe plunger. The needle is grasped with the non-dominant hand and pushed toward the epidural space while the dominant hand (thumb) applies either constant steady pressure, or pulsing intermittent pressure on the syringe plunger. Once the epidural space is entered, the pressure applied to the syringe plunger allows the syringe medium, which may be air or saline or a mixture of both, to flow without resistance into the epidural space [3]. Once the operator detects the LOR and is satisfied that the epidural needle is in place, the syringe is removed and a catheter is threaded through the needle into the epidural space. Finally the needle is carefully removed, leaving the catheter in place to provide medication either through periodic injections, or by continuous infusion.

The epidural space is a very thin layer located between the interspinous ligament and the subarachnoid space which in turn is protected by the dura mater (see Figure 1). The ligamentum flavum is a dense layer of tissue located immediately before the epidural space and presents the greatest resistance to needle advancement. In 2009, Tran *et al.* [4] estimated the average force and syringe pressure required to penetrate the ligamentum flavum in a human subject using the continuous pressure technique and the midline approach. The midline approach involves orientating the needle until it is orthogonal to the patients back and advancing the needle though the interspinous ligament and finally the ligamentum flavum. It was found that the force and pressure applied in the ligamentum flavum was significantly higher than the interspinous ligament. The estimated pressures were calculated to be around 37.5 ± 20.0 kPa for the ligamentum flavum and 15 ± 5.3 kPa for the interspinous ligament [4]. These

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pressure values were assumed as operational pressures for future designs.

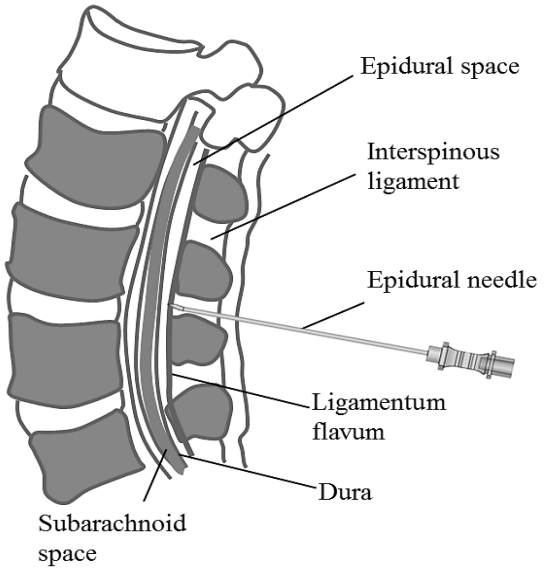

Figure 1 Graphical representation of the epidural space and surrounding anatomy with an epidural needle tip positioned in the epidural space.

Accidental dural puncture (i.e., entry into the subarachnoid space) is the most significant complication associated with regional anaesthesia but the incidence is hugely dependent on clinician experience. For experienced clinicians puncture rates are typically between 1-3% [5]. However, for trainee anaesthetists, the mean epidural failure rate is one in every five consecutive epidurals for the first 50 epidurals performed [6]. Proficiency in the loss-of-resistance technique is difficult to teach or demonstrate. As many as 60 attempts at epidural anaesthesia may be required before a 90% success rate is achieved [7], [8]. The technique may also be unreliable in patients with altered vertebral anatomy or calcified spinal ligaments, while epidural anaesthesia failure rates are greater in obese patients [9]. There is an urgent need to provide confirmation of epidural entry for these novice end-users. The most benign consequence of these so-called 'spinal taps' is severe and prolonged headaches for the patient which occurs in approximately 86% of accidental dural puncture. Patients with severe post-dural puncture headaches may be readmitted and treated with an epidural blood patch leading to additional insurance and healthcare costs [10].

A more common complication of epidural administration is a 'false positive': Based on haptic feedback, the clinician incorrectly assumes the epidural space has been reached. This is more likely to occur in obese patients due to air or saline leakage as the epidural needle passes through layers of fatty tissue giving false LOR feedback. In rare circumstances (<1% [11]), complications associated with the current LOR technique may also include pneumocephalus, spinal cord and nerve root compression, subcutaneous emphysema, venous air embolism, and neurological injury [1].

This work examines the design, bench-top development and pre-clinical investigation of a novel, easy-to-use indication device which provides visual and haptic feedback for needle entry into the epidural space. This device, which shall henceforth be referred to as ProDural, may significantly alleviate the complications associated with identifying the epidural space.

2. Materials and Methods

2.1 Design Criteria

In recent years, developments such as fibre optics [12], ultrasound [13] and products such as Compuflo [14] (employs sensors to detect the pressure drop) and acoustic puncture assist device [15] have been developed to replace the conventional manual LOR technique, but these alternatives have struggled to achieve market penetration due to high up-front investment and clinical inertia. There are a number of competing devices which still avail of the pressure drop technique which include Episure and Epidrum. Both of these devices are "charged" or primed prior to application and automatically retract once the epidural space has been reached. However, this automatic retraction replaces the tactile sensation associated with the LOR technique, thus creating uncertainty of correct needle placement. In 2006, 99% of anaesthetists in the U.K. used some form of the LOR technique to identify the epidural space, be it a continuously applied pressure or a pulsing, intermittent pressure to the syringe plunger (LOR to saline continuous 58%, saline intermittent 16%, air continuous 4% and air intermittent 21%) [16]. Provisional technology examinations and end user surveys rendered a list of design requirements which included the following:

The device must-

- increase the effectiveness of locating the epidural space,
- be cost effective and easy to use,
- maintain the existing LOR techniques whilst reducing the incidence rate of associated complications,
- reduce the steep learning curve associated with epidural administration,
- be capable of implementation in a dimly lit environment without compromising ease of use.

All these features were considered during the design process. An initial concept was first derived from a biomedical design module within University College Cork. Several designs were developed and prototyped subsequently until the final design was recognised through continuous collaboration between clinicians and design engineers. The result (Figure 2) was later tested in both bench-top and pre-clinical investigations.

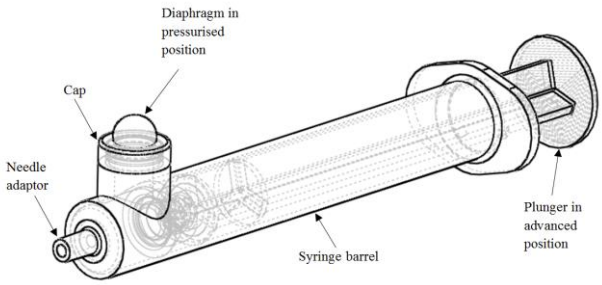

Figure 2 ProDural concept design with visual pressure drop indicator integrated into the distal end of the syringe barrel

2.2 Proposed Solution

The proposed solution comprises an indication device and modified LOR syringe barrel which should provide visual and haptic feedback of needle entry into the epidural space. The indication device further comprises an expandable diaphragm. The intended method of use involves coupling the distal end of the syringe with an epidural needle and advancing both through the interspinous ligament and ligamentum flavum whilst applying intermittent or continuous pressure on the syringe plunger inflating the diaphragm. Visual confirmation of entry into the epidural space will be achieved by the immediate collapse of the inflated diaphragm (see Figure 3).

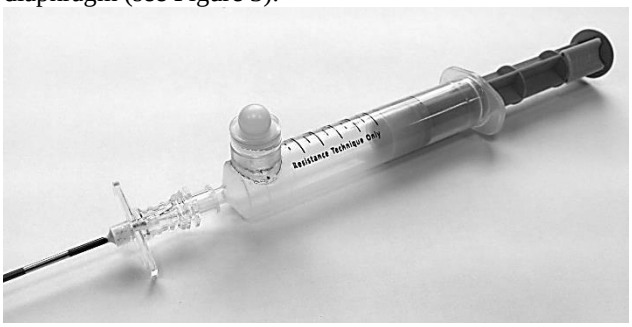

Figure 3 The ProDural prototype used in pre-clinical investigation with the visual indicator distended in the pressurised position.

2.3 Prototype Development

The development cycle for the body of the device involved iterative barrel and plunger design using SolidWorks (Dassault Systèmes SolidWorks Corp., Waltham, MA, USA), which were subsequently developed in-house using a Dimension Elite 3D Printer (Stratasys Ltd., MN, USA) with a resolution of 0.178 mm. The visual indicator which is integrated into the distal end of the syringe barrel was prototyped by machining perspex rods to varying internal and external diameters thus providing a range of possible configurations which were later tested. For the pre-clinical study, the visual indicator was adhered to an existing 7ml LOR syringe (BD Epilor ™, Becton Dickinson, Franklin Lakes, NJ, USA).

Material selection for the diaphragm was critical to the development of this device. For ease of prototype manufacturing and proof of concept, rubber latex was used in the initial prototypes. It is proposed to replace this material with a biocompatible alternative such as synthetic, latex-free polyisoprene or silicone rubber with similar mechanical properties in future work. Three samples of varying thicknesses were evaluated in a model by end users to determine an appropriate material thickness for initial prototype development and for early proof of concept testing. The model used for this evaluation was a banana which is commonly used as a model for initial instruction in epidural catheterisation [17] (see Figure 4). The diaphragm sample was later analysed for compliance though experimental investigations as outlined in Section 2.4.

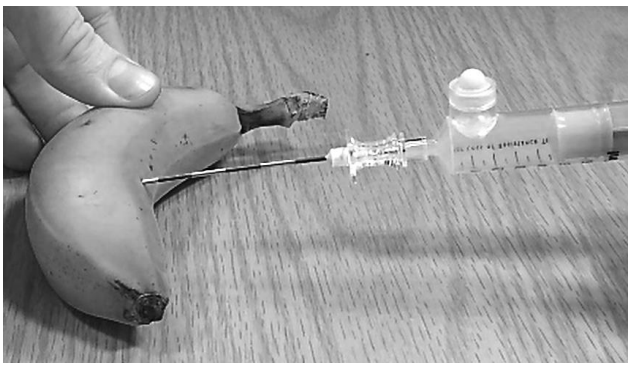

Figure 4 The banana model used in early proof of concept testing. The proximal, dense surface of the banana represents the skin. As the needle advances and passes through the fruit of the banana it is comparable to the interspinous ligament. Finally as the needle reaches the opposite surface of the banana, the change in density is representative of the needle reaching the ligamentum flavum.

2.4 Experimental Investigations

To determine the biaxial characteristics of the elastomer diaphragm, the bubble inflation technique was used [18], [19]. The visual indicator is in fluid communication with a pressure gauge and a manual inflation pump (figure 5).

The bubble inflation pressure was manually controlled by an Encore inflation system (Boston Scientific, Natick, MA). A video camera (resolution of 1980x1080 pixels) recorded the inflation pressure corresponding to the bubble height. Experimental assumptions included truly equi-biaxial stretching at the pole of the bubble, uniform thickness at the pole and planer expansion near the rim. It was also assumed that the balloon would display spherical symmetry throughout its expansion.

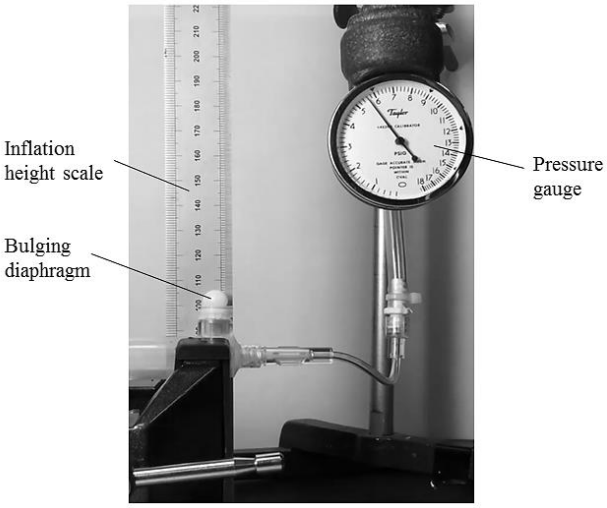

Figure 5 Experimental apparatus to evaluate the biaxial characteristics of latex rubber diaphragm at room temperature (21°C).

Three data sets were taken for a 0.135 mm thick latex diaphragm. The values for each of the data sets were quite consistent varying by less than 10 %. This variance may be a result of strain hardening and permanent deformation as well as experimental error. When evaluating the stress values of a specific material undergoing deformation it is essential to specify if the stress values are to expressed as engineering stress (σ_{eng}) or true stress (σ_{true}). With hyperplastic materials undergoing significant elastic deformation, true stress should be considered to account for changes in cross-sectional area. The relationship of true stress to engineering stress for both uniaxial and equi-biaxial tension [18] can be expressed as:

$$\sigma_{true} / \sigma_{eng} = \lambda \tag{1}$$

where λ is the stretch ratio (elongation ratio) in the direction of the applied load and is expressed as the ratio between the current length l and the initial length of the polar zone l_0:

$$\lambda = \frac{l}{l_0} \tag{2}$$

Engineering stress for the bubble inflation case is a function of pressure P, radius of curvature r_c, original thickness t_0 and stretch ratio λ [18], [20] and can be expressed as:

$$\sigma_{eng} = \frac{Pr_c}{2t_0} \cdot \lambda \tag{3}$$

2.5 Pre-Clinical Investigation

Pre-clinical human cadaveric testing of the current ProDural prototype has been completed by a consultant anaesthetist. This investigation represented a technical assessment of ProDural in locating the epidural space. The primary outcome was experimental validation that the ProDural diaphragm collapses once the epidural space had been reached. ProDural was tested using both air and water as an inflation medium. The secondary outcome was to compare ProDural to existing technologies for (1) amount of fluid injected on reaching the epidural space, (2) ease of use, (3) effectiveness in finding the epidural space, and (4) length of needle insertion. Finally a number of different ProDural prototypes were used varying in diaphragm material and thickness and aperture diameter to determine optimum characteristics based on end user feedback.

Several repeated tests were executed to establish the effectiveness of ProDural at identifying the epidural space in a freshly preserved cadaver. The unembalmed cadaver used in this investigation was that of a 99 year old female. The cadaver was in excellent condition and the vertebral column was intact from the cervical to T11 vertebrae. The spine demonstrated scoliosis consistent with cadaver age. The cadaver was placed in the supine position with a slight right tilt. Using the conventional LOR technique and an 8ml Perifix syringe (B.Braun, Melsungen, Germany), the clinical investigator introduced a needle tip into the subarachnoid space in the region of T5. Once the subarachnoid space was located, a catheter was inserted and methylene blue dye was infused into the subarachnoid space. This approach facilitated investigation of dura puncture where blue dye would become visible on aspiration.

3. Results

3.1 Experimental Results

Camera footage analysis generated the real-time inflation pressure P and corresponding bubble height. r_c and l were determined by arc-fitting to the bubble's radius of curvature using AutoCad software (Autodesk Inc, San Rafael, CA) (Figure 6). The polar surface of the bubble was marked to indicate the elongation of the arc length as the bubble expanded.

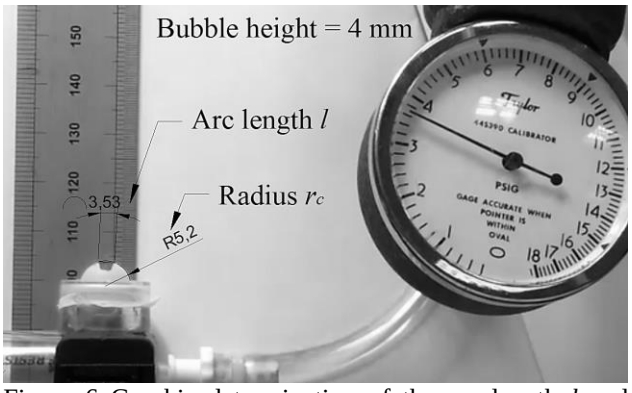

Figure 6 Graphic determination of the arc length l and radius of curvature r_c at a bubble height of 4 mm and corresponding inflation pressure of 25.51 kPa (3.7 psi).

The plot of Figure 7 shows inflation pressure versus stretch ratio and illustrates the behaviour of the latex material as it undergoes bi-axial deformation.

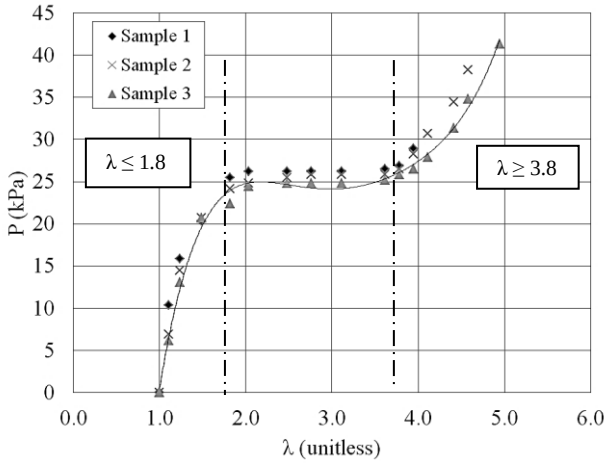

Figure 7 Inflation pressure and elongation ratio relationship for a latex membrane during bi-axial bubble inflation testing.

The elastomer initially demonstrates quasi-linear behavior for small elongations ($\lambda \leq 1.8$). The material then begins to yield as it quickly expands at almost constant pressure. The final domain of large deformation ($\lambda \geq 3.8$) sees the material undergoing strain hardening. Three samples were investigated and the solid line represents the associated best-fit in a least square sense. Based on the findings of Tran *et al.* [4], the membrane would reach the domain of large deformations ($P \approx 37$ kPa, $\lambda \approx 4.7$) when passing through the ligamentum flavum. However this falls short of the burst pressure which was experimentally measured as 62 kPa at an elongation of approximately 960%.

Figure 8 shows the relationship between the true stress and the stretch ratio for three samples of a least square fit of a thin latex diaphragm ($t_0 = 0.135$ mm).

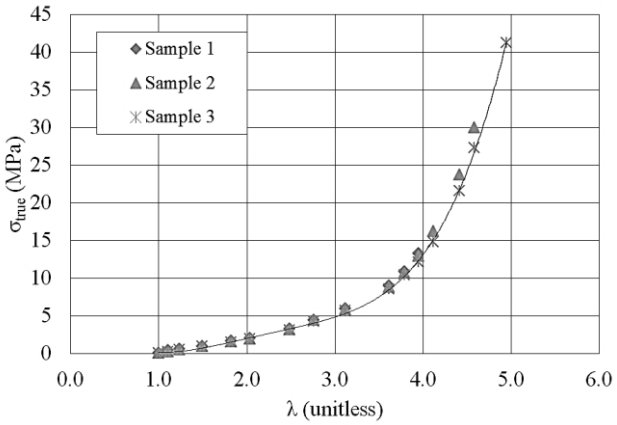

Figure 8 A graphic representation of the relationship between true stress and the stretch ratio.

3.2 Pre-Clinical Investigation Results

The first tests compared ProDural to conventional LOR syringes using both air and water as the inflation medium. An 8 ml Perifix or 7 ml Epilor syringe (Becton Dickinson) was initially used to identify the epidural space. Using the midline approach and a pulsing LOR technique, the clinician identified the epidural space. The needle depth and the amount of air/water injected were recorded. The syringe was then removed and the needle site was aspirated. Blue dye did not become visible on aspiration, therefore it was concluded that the dura had not been punctured. The needle was then removed. The test was repeated in the same region using a ProDural syringe. ProDural was advanced using the midline approach as before until an apparent collapse of the visual indicator was observed (see Figure 9). The needle depth and injected volume of fluid were again recorded. Subsequent aspiration failed to identify blue dye. ProDural was removed and the needle was left in place. The position of the needle was marked as point 1. Succeeding dissection would demonstrate whether or not the needle at this point punctured the dura. This test was subsequently repeated at different regions along the spinal column.

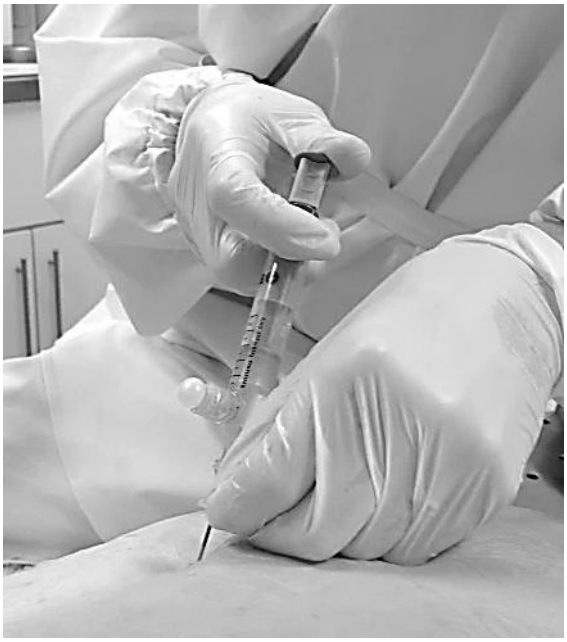

Figure 9 ProDural prototype used in pre-clinical cadaveric trial in its inflated state advancing towards the epidural space.

The device was found to be at least as effective and easy to use as a conventional LOR syringe. In both the air and water tests, ProDural introduced less fluid on detection of loss of resistance (65 % reduction) and was subsequently proven to have reached the epidural space without puncturing the dura by means of exposing the needle tip through dissection. The immediate collapse of the visual indicator improved the reaction time of the user preventing excessive advancement of the plunger and epidural needle. Clinical feedback cited a bright colour (e.g., green or yellow) as preferable for the diaphragm. In most cases, the epidural is administered in a dark labour ward in the middle of the night, and bright colours would aid in the detection compared to more neutral colours. It was found that thinner membranes performed better due

to the smoother transition from the elastic to plastic states. The diameter of the diaphragm played little role in performance and may be refined to look most appealing to the end user. There were several shortcomings in the investigation. The model used was not optimum due to the age and absence of the lumbar region. As the investigation progressed, it proved increasingly difficult to determine the epidural space due to the degrading effect of repeatedly introducing needles and it was not possible to carry out several repeat tests along the vertebral column. Notwithstanding these limitations, the study indicated that ProDural represents a very promising device for identifying the epidural space. More studies are necessary to determine if ProDural can effectively reduce rates of accidental dural puncture or 'false positive' rates.

4. Conclusion and Future Work

The goal of this work was to design and develop a medical device which can advance the efficacy of epidural administration. With over 2.76 million patients receiving epidural or spinal anaesthesia during labour in the US alone, it is of paramount importance to identify a more reliable method of epidural administration. The ProDural device maintains the popular tactile feedback associated with the LOR technique whilst potentially enhancing operational performance through an integrated visual pressure drop detector.

The instantaneous collapse of the diaphragm may improve the clinician's reaction time thus preventing excessive needle advancement and reducing the risk of accidental dural puncture. ProDural may also reduce the risk of false positive readings in obese patients as the clinician may vary the applied pressure to determine when the epidural space has been reached. The contrasting bright surface of the diaphragm ensures clear visibility even in a dimly lit maternity ward. Finally, ProDural may reduce the steep learning curve associated with epidural administration as the bulging diaphragm allows teaching clinicians to visually determine correct placement by their trainee doctors.

While the results of this preliminary analysis and experimentation are encouraging, a clinical investigation will be required to investigate whether or not ProDural can statistically reduce the incidence rate of accidental dural puncture and false positive readings. The mechanical experiments defined the relationships between the inflation pressure and true stress and stretch ratio for the current device configuration. It was found that the pressure required to penetrate the ligamentum flavum determined by Tran *et al.* [4] is significantly less than the burst pressure by a factor of approximately 1.7. The pre-clinical study served as a technical feasibility evaluation verifying the proof of concept and suggested that ProDural is at least as effective and easy to use as existing LOR syringes. The most significant advancement noted in the study is the improved reaction time on reaching the epidural space. This may reduce the risk of accidental dural puncture and consequently reduce costs to the healthcare provider due to shorter hospital stays. It was also demonstrated that ProDural introduced less volume of injection fluid that would otherwise dilute subsequent anaesthesia and may cause air embolisms and or other complications [1], [21].

Future work is required before ProDural may be evaluated in a live human investigation. The operational nature of ProDural is one that requires a smooth transition from the original undisturbed diaphragm position to the inflated state ($\lambda \approx 4$). The highly elastic nature of natural rubber latex with an elastic modulus of between 1 and 5 MPa is ideal for the disposable, short term requirements of ProDural. However, latex contains proteins and chemical allergens which make it unsuitable as a material for medical devices. It is therefore proposed to replace the latex material with a biocompatible alternative with similar characteristics illustrated in Figures 7 and 8 such as latex-free synthetic polyisoprene. Pending these important investigations and modifications, the current results point to a promising alternative epidural space location device which has the potential to help alleviate complications and cost in epidural administration.

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