Validation of the soft-embalmed Thiel cadaver as a high-fidelity simulator of pressure during targeted nerve injection

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ABSTRACT

Introduction Although administration of regional anesthesia nerve blocks has increased during the COVID-19 pandemic, training opportunities in regional anesthesia have reduced. Simulation training may enhance skills, but simulators must be accurate enough for trainees to engage in a realistic way—for example, detection of excessive injection pressure. The soft-embalmed Thiel cadaver is a life-like, durable simulator that is used for dedicated practice and mastery learning training in regional anesthesia. We hypothesized that injection opening pressure in perineural tissue, at epineurium and in subepineurium were similar to opening pressures measured in experimental animals, fresh frozen cadavers, glycol soft-fix cadavers and patients.

Methods We systematically reviewed historical data, then conducted three validation studies delivering a 0.5 mL hydrocolloid bolus of embalming fluid and recording injection pressure. First, we delivered the bolus at 12 mL/min at epimysium, perineural tissue, epineurium and in subepineurium at 48 peripheral nerve sites on three cadavers. Second, we delivered the bolus at using three infusion rates: 1 mL/min, 6 mL/min and 12 mL/min on epineurium at 70 peripheral nerve sites on five cadavers. Third, we repeated three injections (12 mL/min) at 24 epineural sites over the median and sciatic nerves of three cadavers.

Results Mean (95%) injection pressure was greater at epineurium compared with subepineurium (geometric ratio 1.2 (95% CI: 0.9 to 1.6)), p=0.04, and perineural tissue (geometric ratio 5.1 (95% CI: 3.7 to 7.0)), p<0.0001. Mean (95%) injection pressure was greater at 12 mL/min compared with 1 mL/min (geometric ratio 1.6 (95% CI: 1.2 to 2.1)), p=0.005. Pressure measurements were similar in study 3 (p>0.05 for all comparisons).

Discussion We conclude that the soft-embalmed Thiel cadaver is a realistic simulator of injection opening pressure.

INTRODUCTION

Regional anesthesia is recommended for patients either with or suspected COVID-19 infection, in order to avoid general anesthesia and protect healthcare staff from aerosol generation of respiratory droplets during airway manipulation. However, our department’s policy during the pandemic is that anesthesia, including regional block, should be provided by the most experienced anesthesiologist available in order to provide high-quality care and minimize the risk of conversion to general anesthesia. More regional anesthesia has been performed during the pandemic, but not by trainees who have provided support to extended intensive care units.

There is a pressing need to train anesthesiologists in regional anesthesia skills. Both low-fidelity and high-fidelity simulators show benefit, but must be accurate enough for participants to engage in a life-like way in order to correctly position the tip of the needle relative to the target nerve and experience the realistic ranges of injection pressures. The benefit of high-fidelity replication of pressure, as well other features such as elasticity, resilience and durability, is that it enables deliberate practice—the repetition and successive refinement of performance, a cornerstone of the expert-performance approach to skills training.

The soft-embalmed Thiel cadaver is the training simulator used at the European Society of Regional Anesthesia cadaver training course in Madrid. It possesses many features of a high-fidelity simulator: physical properties and functionality of cadavers are similar to patients, patient dimensions and anatomical variation reflect clinical practice and ultrasonic imaging of tissues and needles is realistic. Nerve histology approximates that of humans. Tissue elasticity is retained and confers several benefits. Perineural injection distends then relaxes tissue within the same timeframe as during injection of local anesthetic during clinical nerve block. Ventilation is possible using inflation pressures <20 cm H2O (1.96 kPa). Resilience has been consistently demonstrated: hundreds of injections are possible with only minimal tissue disruption, needle tracks are not seen and multiple puncture points in skin are not apparent.

Realistic replication of injection pressure at tissue interfaces, as well as within nerves, is particularly important for detecting the precise location of the needle tip because high subperineural fluid injection pressure is a recognized factor in the genesis of nerve injury and fluid injection pressure >103 kPa (15 psi) is a sensitive means of differentiating between epineural contact and perineural needle tip placement in patients.

Cadaver validation is also essential for research. New block techniques may be tested and imaged within a safe environment; new ultrasound and needle technologies developed and tested and...
device regulatory studies conducted without the need for animal experimentation.

Our initial objective was to review the literature pertaining to measurement of injection pressure in anaesthetized dogs,16 17 pigs,18 19 fresh frozen cadavers,20–22 phenol/glycol cadavers23 24 and patients.14 15

We then conducted three separate studies in order to validate characteristics of pressure measurement observed in the aforementioned studies, notably discrimination between needle tip tissue location14–16 and correlation between fluid injection rate and opening pressure.15 23 24 Therefore, the objective of the first study was to compare opening injection pressure, on epimysium, in perineural tissue, at epineurium and in subepineurium. The objective of the second study was to validate the linear relationship between opening injection pressure and flow rate. We also conducted a third study in order to investigate whether opening injection pressure measurement was repeatable at the same site.

METHODS

We reviewed the literature pertaining to measurement of injection pressure in animals, cadavers and patients. We searched MEDLINE, Embase, CINAHL databases and registers of ongoing trials (www.clinicaltrials.gov and www.controlled-trials.com) in order to identify all published papers investigating pressure measurement at nerves. We used the guidelines for systematic reviews provided by the International Prospective Register of Systematic Reviews.27 Our review question was: ‘does in-line pressure measurement differentiate between needle tip position?’ We searched the Cochrane Central Register of Controlled Trials in the Cochrane Library, Embase, MEDLINE, EBSCOhost and Web of Science.

We used the medical subject headings search term ‘nerve block’, with free text ‘pressure’, ‘ultrasonography’, ‘peripheral nerves’, ‘nerve’, ‘fascicle’, ‘epimysium’, ‘perineural’, ‘epineurium’, ‘epimysial’, ‘extraneural’ and ‘intraneural’. One author (GML) performed the search and collated the studies. The types of studies included were randomized trials and observational studies comparing in-line opening pressure measurement either in perineural tissue, at epineurium, within subepineurium or in subperineurium (within fascicles). Our primary outcome was opening pressure. Secondary outcomes included covariates such as injection model (animal, cadaver or patient); nerves targeted; infusion rate and the relative proportion of injections< or ≥15 psi (103 kPa). Data were expressed as mean (SD) and range noted where available.

We then conducted three experiments at the Centre for Anatomy and Human Identification, University of Dundee, UK, in order to validate opening pressure measurements on human soft-embalmed cadavers. Written permission was given by the Thiel cadaver advisory committee. The senior anatomy technician chose 12 cadavers that had completed at least 6 months soft embalming. The first cadaver was used for training the operators and ensuring they were comfortable with needleling and ultrasound techniques before starting the study. The remaining 11 cadavers were distributed among three studies.

For all three studies, a 100 mm 21 g nerve block needle (Stimuplex, B. Braun, Melsungen, Germany) was connected in line to a fluid pressure sensor (P-MAT, PendoTech, New Jersey) with a measurement range up to 517 kPa (75 psi) and to a 30 mL syringe driven by an automated infusion device (PHD Ultra, Harvard Instruments, Holliston, Massachusetts). The infusion device was programmed to deliver a 0.5 mL bolus of Thiel embalming fluid at controlled rate. We used a 0.5 mL hydrolocation bolus in our routine clinical practice in order to confirm the position of the tip of the block needle. The microultrasound imaging system and P-MAT system were time synchronized, and pressure data were measured at a rate of 0.5 Hz.

Study 1: injection fluid pressure versus needle tip position

The primary objective of the first study was to compare opening fluid injection pressure when the needle tip was within perineural tissue, on contact with epineurium and within subepineurium. We hypothesized, based on our previous work on anaesthetized pigs,28 that opening fluid injection pressure at epineurium was greater than that at perineural and subepineurial needle locations. We also decided to measure opening pressure on indenta- tion of the epimysium of muscle. The epimysium is distinct on ultrasound imaging and provides resistance to needle penetration, but is rarely evaluated. Thus, we anticipated that our study would provide data on all significant tissues potentially encountered by needles during cadaver training and research.

We imaged and targeted 48 upper and lower limb nerve sites on three soft-embalmed Thiel cadavers (nos 2–4), with the order of injection randomized by computer software to the left and right sides of eight nerves and two operators, a consultant and a fellow in regional anesthesia (figure 1). Nerves were imaged using a 3–8 MHz linear ultrasound transducer connected to a Zonare Ultra ultrasound machine (Zonare, Mountain View, California). This is the transducer dedicated to imaging anatomical structures in Thiel cadavers.

The nerves imaged were: the C5 and C6 ventral nerve roots, mid-forearm median and ulnar nerves, the femoral nerve, popliteal tibial nerve and mid and proximal thigh sciatic nerves. The C5 and C6 ventral nerve roots were identified medial to the scalenus medius muscle. Forearm nerves were imaged in the fascial plane between the superficial and deep flexor muscles. The median nerve was located medial to the flexor carpi radialis, and the ulnar nerve was located lateral to the flexor carpi ulnaris muscle. The femoral nerve was imaged in the groin beneath the sartorius muscle and fascia iliaca. The popliteal tibial nerve and sciatic nerve sites were located medial to biceps femoris and lateral to semitendinosus and semimembranosus. All needles were inserted using an in-plane approach and penetrated the aforementioned muscle groups.

We indented epimysium and epineurium with needles using the same method described by Gadsden et al.14 15 The needle tip position was confirmed on ultrasound images by both operators, and the times of injection were recorded by an independent research assistant.

We were aware from previous studies that direct placement of needles against epineurium is difficult, nerves are pushed backwards and rotate and needles tend to veer tangentially. Therefore, if the needle or the nerve slipped away during injection, the operator repeated the procedure, by removal of the needle and reinsertion through skin.

Study 2: injection fluid pressure versus infusion rate

The objective of the second experiment was to investigate the effect of infusion rate on fluid injection pressure when the needle tip was in contact with epineurium. The flowchart is shown in figure 1. Two operators scanned nerves using a 22–45 MHz UHF48 microultrasound transducer attached to a FUJIFILM VisualSonics Vevo MD ultrasound machine (VisualSonics, Amsterdam, the Netherlands) that is used clinically for neonatology, vascular imaging and dermatology. This imaging system provides high-quality images of structures up to 2 cm from the...
skin, so restricted us to imaging seven superficial nerves on both sides of five soft-embalmed Thiel cadavers (nos 5–9). Nerves included the C5 and C6 nerve roots, axillary median and radial nerves, forearm median and ulnar nerves and the popliteal tibial nerve. The approach to the nerve roots, forearm and femoral nerves was the same as that employed in the first study. The axillary median and radial nerves were visualized in the axilla, lateral and inferior, respectively, to the axillary artery. The latter was visualized as a small anechogenic area.

The operators consisted of an experienced regional anesthesiologist and a PhD student trained previously in regional anesthesia nerve block on the soft-embalmed Thiel cadaver. The PhD student was trained repeatedly on cadaver 1 by the primary investigator until she had demonstrated competencies equivalent to trainee anesthesiologists at the end of basic training, defined by the Royal College of Anaesthetists 2010 curriculum. The procedure consisted of percutaneous insertion and indention of the epineurium of the targeted nerve as described above.

Figure 1  Flow chart. Flow diagrams for the three studies replicating peripheral nerve blocks on Thiel embalmed cadavers showing selection of nerves for intervention sites. C5, C6, ventral cervical nerve roots; fem, femoral nerve; Med Ax, rad Ax, axillary median and radial nerves; Med, Uln, mid forearm median and ulnar nerves; Sci-M, Sci-U, mid and upper (proximal) sciatic nerve; Tib-P: popliteal tibial nerve.
The pressure measurement setup was the same as in study 1. We used three infusion rates, 1 mL/min, 6 mL/min and 12 mL/min, in order to deliver the 0.5 mL fluid bolus. However, the number of blocks was restricted by the number of cadavers and superficial injection sites we had available. Therefore, we decided to randomize to 28 injections at 6 mL/min and 28 injections at 12 mL/min, in order to maximize data from clinically relevant flow rates. We also performed 14 control injections at a subclinical flow rate of 1 mL/min over 30s. This acted as a control measure that gave us three widely separated flow rates to chart against opening pressure. These flow rates mirrored those used in an anaesthetized pig study with 40 MHz micro-ultrasound to identify nerves clearly, and thus offered us the opportunity to directly validate the relationship between flow and pressure in cadavers against that observed in anaesthetized pigs.

**Study 3: repeated injection**

We conducted a third study to evaluate the effect of repeated injection by the same operator on opening pressure measurements at epineurium. The pressure recording setup was the same as that used in the two previous studies. The flowchart is shown in figure 1. The order of injections were randomized equally between the proximal and distal sites of median and sciatic nerves on both sides of three cadavers (nos 10–12), for a total of 24 procedure sites. The proximal median nerve site lay between the biceps femoris and brachialis muscle adjacent to the brachial artery, and the mid-arm site was medial to the flexor carpi radialis. Needle insertion sites were approximately 15 cm apart. The proximal sciatic nerve site was identified on ultrasound inferior to a line intersecting the greater trochanter and ischial tuberosity. The distal site corresponded to the apex of the popliteal fossa. At both sites, the sciatic nerve lay between the biceps femoris laterally and the semitendinosus and semimembranosus medially.

A single experienced operator inserted a 100 mm 21 g nerve block needle (Stimuplex, B. Braun, Melsungen, Germany) from the lateral side through biceps femoris towards the nerve target and indented the epimysium and nerve epineurium in the same fashion as preceding studies. A 0.5 mL hydrolocation dose was injected and pressure trace was recorded. Epineural injections were repeated three times as separate procedures. On each occasion, the needle was withdrawn completely from the skin then reinserted. On the third occasion, the operator attempted to penetrate the epineurium with the needle, entered the nerve and performed the injection. If the operator had difficulty recognizing intraneural swelling, then intraneural injection was repeated.

The secondary objectives of all studies were to investigate the effect of nerve site, cadaver, left and right sides and operators on fluid injection pressure.

**Statistical analysis**

The maximum pressure measured over the duration of the injection was taken as the opening injection pressure. The distribution of the opening pressure data was assessed using the D’Agostino-Pearson omnibus K² test (GraphPad Prism V8.2.0, GraphPad Software, San Diego, California) and we used quartile–quartile plots to visualize fit to normal and lognormal distributions. We log converted pressure data and used a mixed effects regression model to analyze paired data and model our covariates against fascial, epineural and intraneural fluid injection pressures. All pressures were considered as intention-to-treat data and were used for analysis. Items were compared using individual comparison hypothesis tests. Results are expressed as geometric mean (95% CI).

For study 1, power analysis was based on comparison of paired, dependent fluid pressure data at epineurium and during intraneural injection. From a previous anaesthetized pig experiment, we assumed an effect size of 0.5 and two-tailed test with $\alpha=0.05$ and $\beta=0.90$. We calculated (G*Power, University of Dusseldorf) that we needed at least 22 paired measurements. Given that eight injections were performed on each side of the cadaver, we used three cadavers and administered 48 injections.

Study 2 was powered on the correlation of three injection rates. We assumed an effect size of 0.5 and two-tailed test with $\alpha=0.025$ and $\beta=0.90$. We used $\alpha=0.025$ because we were comparing three groups. We needed 68 injections and therefore conducted 70 injections on five cadavers (seven injections per side per cadaver).

In order to power study 3, we hypothesized that there would be no difference in opening pressure during repeated injections at epineurium. We powered the study based on the difference between means being less than half the common SD (equivalent to an effect size=0.5). Using a two-tailed test with $\alpha=0.025$ and $\beta=0.90$ for three paired groups, we calculated that we needed at least 52 injections. We therefore randomized to a total of 72 injections on epineurium. This consisted of 24 injections (two per limb per side of three cadavers) repeated three times.

**RESULTS**

Table 1 summarizes studies measuring pressure at subepineural sites in dogs, pigs, fresh frozen and soft fix cadavers, as well as pressures encountered on needle–nerve contact on patients.

**Study 1: needle insertion and injection at fascia, epineurium and in subepineurium**

Figure 2 shows representative ultrasound images of needle insertion, tissues and target nerve.

The median range time from first embalming was 6 (6–7) months for cadavers 2–4. Injections were performed at 48 nerve sites. We failed to enter nerves on three occasions. On 11 occasions, the nerve rotated and the needle was directed tangentially. These injections were repeated successfully giving 56 pressure measurements at epineurium for analysis. Injection at epimysium was identified on 84 occasions.

Pressure data had a lognormal distribution (figure 3). All perineural pressures were <103 kPa (15 psi). Pressures >103 kPa (15 psi) was recorded on 36 (64%) occasions at epineurium, 22 (49%) occasions in subepineurium and on 46 (55%) occasions at epimysium. Opening pressure was higher at epineurium compared with perineural tissue (geometric ratio 5.1 (95% CI: 3.7 to 7.0)), p<0.0001, epimysium (geometric ratio 1.3 (95% CI: 1.0 to 1.6)), p<0.006, and subepineurium (geometric ratio 1.2 (95% CI: 0.9 to 1.6)), p=0.04 (figure 3B,C). Opening pressure in subepineurium was greater than that in perineural tissues (geometric ratio 4.2 (95% CI: 3.0 to 5.0)), p<0.0001. There was no difference in opening pressure between nerves (figure 3D).

Superimposed pressure/time plots at epimysium, in perineural tissue, on epineurium and in subepineurium are over the midsciatric nerve, femoral nerve, ulnar nerve and popliteal nerve. Images demonstrate variation in relative pressures measured at different interfaces. For example, figure 3A shows a rank order of pressure: epineurium > epimysium > subepineurium > perineural tissue, whereas figure 3B shows higher pressures during
### Table 1  Summary of pressure studies in dogs, pigs, fresh frozen cadavers, phenol/glycol cadavers and patients

| Author          | Species/model | Nerve(s)               | Infusion rate (mL/min) | Volume (mL) | Injection (n) | Subperineural | Subepineural | Epineural | Perineural | Comments                      |
|-----------------|---------------|------------------------|------------------------|-------------|---------------|---------------|---------------|-----------|-----------|--------------------------------|
| Haidzic et al²⁶ | Dog           | Sciatic                | 4                      | 4           | 14            | 150 (117) (21–310) | 22 (17) (3–45) | 21 (6)    | 3 (1)     | Intraneural: 57%>172 kPa (25 psi) All perineural<28 kPa (4 psi) |
| Kapur et al²⁶  | Dog           | Sciatic                | 4                      | 4           | 20            | 207 (48) (14–262)  | 30 (7) (2–38)  | 55 (21)   | 8 (3)     | Intraneural: 40%>75 kPa (11 psi)  |
| Lupu et al²⁶   | Pig           | Median—forearm         | 15                     | 10–20       | 20            | 35 (20) (2–35)  | 5 (3) (2–9)   | 100%<103 kPa (1.5 psi) |
| Altematt et al³⁹ | Pig          | Brachial plexus Femoral | 4                      | 24          |              | 48 (55) (0–221)  | 7 (8) (0–32)   | 20%>103 kPa (1.5 psi) |
| Orebaugh et al³⁹ | Fresh cadaver | Cervical roots         | 20                     | 5           | 8             | 337 (69) (2.55–455) | 49 (2.5) (3.7–66) | 100%>103 kPa (1.5 psi) |
| Ross et al³⁸   | Fresh cadaver | Cervical roots Peripheral nerves (MC and ulnar in axilla, median and radial in arm, femorals) | 20         | 5           | 14            | 415 (119) 2.25 (97) | 60 (17) 33 (14) | 148 (59) 22 (9) |
| Vemeylen et al³⁹ | Fresh cadaver | Femoral Saphenous Sciatic Tibial Common peroneal | 10         | 10          | 100           | 157 (33) 22 (5) | 152 (18) 22 (3) | 172 (34) 25 (5) | 151 (34) 22 (5) | 181 (30) 26 (4) | 27 (6) 4 (1) 100%>103 kPa (1.5 psi) |
| Kroil et al³³  | Phenol cadaver | Median Radial Ulnar | 6                      | 1           | 60            | 206 (65) 29 (9) | 191 (60) 27 (9) | 125 (49) 18 (7) | 7 (3) 8 (3) 7 (2) |
| Kroil et al³⁴  | Phenol cadaver | Cervical trunk Supraventricular Intraventricular Sciatic Peroneal Tibial | 6         | 1           | 30            | 218 (42) 31 (6) | 168 (105) 24 (15) | 166 (67) 23 (10) | 158 (62) 23 (8) | 138 (25) 20 (4) | 120 (51) 17 (7) | 6 (2) 6 (2) 7 (2) 87%>103 kPa (1.5 psi) |
| Gadsden et al⁵  | Patient       | Femoral | 10         | 1           | 20            | 102 (1/6) (83–131) | 15 (2) (12–19) | 90%>103 kPa (1.5 psi) |
| Gadsden et al⁵  | Patient       | Interscalene           | 10                     | 1           | 36            | 145 (44) 21 (4) | 97%>103 kPa (1.5 psi) |

Data are presented as mean (SD) and (range) if available from published article. MC, musculocutaneous.
subepineural injection. Baseline pressure varied between 0.5 psi and 1.5 psi, but remained constant for subsequent injections, including subepineural injection, and returned to preinjection levels on tissue relaxation.

**Study 2: fluid injection flow rate**
Median (range) time from first embalming was 6 (6–8) months for cadaver nos 5–9. Figure 4 shows microultrasound images of a block needle approaching and indenting the right interscalene C5 and C6 ventral nerve roots of cadaver no. 8. The image depth is 15.5 mm and thus nerve roots appear larger than seen on standard ultrasound images.

Seventy injections were performed with the needle tip on the epineurium. Overall, 8 out of 70 (11%) epineural pressures were >103 kPa (15 psi). The distributions of pressure measurements were lognormal (figure 5A,B). Mean pressure was greater using a flow rate of 12 mL/min compared with a flow rate of 1 mL/min (geometric ratio 1.6 (95% CI: 1.2 to 2.1), p=0.005).

**Study 3: repeated injection**
Median (range) time from first embalming was 7 (7–8) months for cadaver nos 10–12. At 22 out of 24 sites, we successfully indented epineurium three times. At two sites successfully indented epineurium on two occasions, giving 70 epineural injections for analysis. Opening pressure at epimysium was recorded on 68 occasions. We attempted 30 intraneural injections. Six were repeated at the same site, because the operator had difficulty recognizing uniform nerve swelling expected following intraneural injection.

Sixty-five (93%) epineural pressures were >103 kPa (15 psi). Data were lognormal. There was no difference in pressure between repeated injections on epineural contact with median and sciatic nerves, at either proximal or distal sites (all p values>0.05), figure 5C.

Fluid pressure was greater at epineurium than epimysium (geometric ratio 1.3 (95% CI: 1.1 to 1.5), p<0.001) and greater at epineurium than subepineural injection (geometric ratio 1.8 (95% CI: 1.5 to 2.2), p=0.002).

**Secondary endpoints**
Mixed models analysis showed no statistical difference in fluid pressure between cadavers, nerves and side of injection or between injection sites in studies 1, 2 and 3 (all p values>0.05).

**DISCUSSION**
Together, our studies show that the soft-embalmed Thiel cadaver is high-fidelity simulator of fluid injection pressure. Opening pressure was consistently higher at epineurium than fluid pressure at perineural tissue and during subepineural injection. Opening injection pressure increased with flow rate. Opening pressure on epineurium did not change with repeated injection. No differences were seen in fluid injection pressure between nerves, sites of injection, cadavers, sides and operators.

The magnitude and range of pressures varied at each anatomical location within our three experiments, but remained within the values obtained from previous studies conducted in unembalmed cadavers, glycol/phenol preserved cadavers, pigs, dogs and patients (table 1). Indeed, subepineural injection was well tolerated by human cadavers, as evidenced by the lack of adverse events observed in our study.
pressures were closest to those obtained in pigs29 and epineural pressures were closest to those obtained in patients.14 15

We used a 0.5 mL injection bolus to mimic bolus test doses, a smaller volume than prior studies, and may explain the smaller fraction of epineural pressures that exceed the 103 kPa (15 psi) threshold measured in patients.14 Nevertheless, we feel that our study is clinically relevant because a 0.5 mL volume is commonly used as a hydrolocation dose by regional anesthesiologists and, imaged by microultrasound, is associated with marked traumatic changes in nerve structure.29 We intend to use a larger bolus in future studies in order to examine the dose response of cadaver tissue.

There was a considerable overlap of pressure data between anatomical locations. Overall, the rank order of fluid pressure at tissue may be summarized as epineural>subepineural=epimy- sium>perineural. Baseline pressure at the start of perineural, epineural and subepineural injection was raised between 0.5 psi and 1.5 psi. We suspect that small fluid retention occurred in tissues but was not visible on ultrasound images. Importantly, baseline fluid injection pressure did not rise with repeated injections, indicating that fluid was dissipating away from the site of injection. We cannot explain, however, why subepineural injection started from a slightly raised baseline as we would not expect 0.5 mL extraneural injection to influence intraneural injection. Irrespec- tive, use of repeated injections replicated our clinical practice of delivering hydrolocation doses in order to gauge the position of the needle tip relative to tissue.

Our findings may be explained by examination of the distribu- tion of data. We demonstrated that fluid pressures at all anatom- ical sites in all studies followed the lognormal distribution, a scattering of data common in nature that describes many biolog- ical processes. In order to confirm this finding, we log converted all pressure data and subsequently demonstrated a normal distri- bution from all anatomical sites (figure 3).

The lognormal distribution may be understood by consider - ation of the elasticity of tissue in homogenous, isotropic tissue. Force or stress applied perpendicular to tissue induces a strain or relative displacement that is linear over a very small increment...
We use soft-embalmed Thiel cadavers as simulators for teaching, training and research. The Thiel embalming process was developed as a method to preserve tissues while retaining elasticity joint motion, and life-like coloring of tissues. The cadavers are soaked for 6 months in large vats containing water-based solutions of salts and acids, a process which makes the cadavers aseptic. The cadavers can be stored for up to 3 years and are regulated by the Anatomy Act 2006 (Scotland). The functionality of the soft-embalmed cadaver has enabled us to change the way we train in regional anesthesia. We use dedicated, repetitive practice and mastery learning and quantitative measurement of learning curves using validated task and error checklists.

Weaknesses of study

The principal weakness of the study is that we used a commercial pressure monitor used in previous studies that sampled at only 0.5 Hz. There is a risk with such response rates that true peak pressures are missed. We have adapted a similar commercial pressure monitor to gather data at 10 Hz and will use this in future studies. Moreover, accurate needle–nerve contact was restricted by the resolution of the 5–12 MHz ultrasound transducers and accounts for the need for 11 repeated injections in study 1 and 6 extra subepineural injections in study 3. Interestingly, we had no technical issues in study 2 because we were using a 22–45 MHz ultrasound transducer that offered better resolution of the nerve and permitted better needle orientation and needle tip placement to align the needle tip perpendicular to the epineurium. Microultrasound, defined as ultrasound transducer frequencies ≥30 MHz, is now clinically available and is used to image neonates and children. Use of high frequencies means that only tissue lying within 15 mm from the skin surface can be visualized with greater resolution than standard 10–15 MHz transducers normally used in regional anesthesia. Loss of muscle mass in the elderly means that many peripheral nerves are visible at these distances within soft-embalmed cadavers. Our images in figure 4 have a depth of 13.5 mm and provide an enlarged representation of the intercalane nerve roots. We feel that this technology would enhance pediatric regional anesthesia.

Pressure may be measured at the tip of the needle but this technology is not yet available for clinical use. In the meantime, we hypothesize that the detection of subepineural injection using in-line pressure monitoring is associated with a substantial false negative rate, although that, according to our results, detection of epineural contact is probably more accurate.

CONCLUSIONS

A picture is emerging of a life-like simulator that possesses not only similar elasticity to patients and imitates the flow of local anesthetic around nerves but also replicates the pressures encountered in patients, animals and fresh cadavers during epineural and subepineural injection. Overall, our evidence suggests that the soft-embalmed cadaver provides a realistic simulation environment that can be used for a variety of purposes including simulation-based training of nerve block to anaesthetologists. We see many potential benefits to availability of a high-fidelity simulator include learning skills before undertaking them in supervised clinical practice; testing proficiency as anaesthetists move from novice learners to experts; practising non-technical skills out with the operating theater; evaluating training approaches; research in developing new block techniques; developing and evaluating new technology and offering a model for device regulation without animal experimentation.

Correction notice This article has been corrected since it published Online First. Figure 5 has been replaced.

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