Best Practice & Research Clinical Anaesthesiology 33 (2019) 23–35

Contents lists available at ScienceDirect

Best Practice & Research Clinical Anaesthesiology

journal homepage: www.elsevier.com/locate/bean

2

Novel nerve imaging and regional anesthesia, bio-impedance and the future

Brian D. O'Donnell, MB, MSc, MD, FCARCSI, Consultant anaesthesiologist [a, b, *],
Frank Loughnane, MB, FCARCSI, Consultant anaesthesiologist [a, b, 1]

[a] Department of Anaesthesiology, BreastCheck & Cork University Hospital, Wilton Road, Cork, Ireland
[b] Director Cork Academy of Regional Anaesthesia, Ground Floor, Tara House, Washington Street West, Cork, Ireland

Keywords:
ultrasonography
nerve block
safety
education
bioimpedance
pressure

Ultrasound technology has transformed the practice of regional anaesthesia. Anaesthesiologists routinely use real-time images to guide needle and local anaesthetic placement adjacent to nerves. It is widely accepted that the era of ultrasonography has improved peripheral nerve block success rates and lessened the dose of local anaesthetic required to achieve success. Contemporary reports of harm in relation to nerve injury or local anaesthetic systemic toxicity are reassuring. The safety and efficacy of regional anaesthesia have thus been enhanced.

Ultrasound guidance is, however, not a panacea. Ultrasound guidance requires the development of complex psychomotor skills. Harm may still occur where the needle or local anaesthetic is misplaced, resulting in nerve injury, vascular injury or local anaesthetic systemic toxicity. Advances in both imaging and needle technology may further enhance the safety and efficacy of ultrasound-guided regional anaesthesia. This review will focus on peer review literature to characterise the clinical challenges and explore the potential solutions.

* Corresponding author. Department of Anaesthesiology, BreastCheck & Cork University Hospital, Wilton Road, Cork, Ireland. Fax: +021 4546434.
E-mail addresses: briodnl@gmail.com (B.D. O'Donnell), frankloughnane@gmail.com (F. Loughnane).
[1] Fax: +021 4546434.

https://doi.org/10.1016/j.bpa.2019.02.001
1521-6896/

"Sooner or later someone will make a sufficiently close examination of the anatomy involved, so that exact techniques will be developed." Alon P. Winnie [1].

Introduction

Regional anaesthesia, or more specifically peripheral nerve block (PNB), is a simple concept. By placing a sodium channel blocking agent (local anaesthetic) adjacent to a sensory nerve, action potentials do not occur upon nociceptive stimulation. Signal transmission from the nociceptor to the dorsal root ganglion, dorsal column, spinothalamic tract and ultimately the sensory cortex is disrupted. The person is rendered insensate in the distribution of the target nerve(s). It is therefore possible to interrupt the nociceptive pain pathway and facilitate painful surgery without obtunding consciousness.

PNB anaesthesia is in a process of continuous evolution. Techniques and technologies have slowly evolved over the past 130 years from the first reports of topical ocular anaesthesia [2] and infiltrative techniques using paraesthesia [3]. The use of insulated hypodermic needles and electrical stimulation in regional anaesthesia was reported in the 1950s and1960s, respectively [4,5]. The earliest report of ultrasound technology to guide needle placement during regional anaesthesia came in 1978 when Le Grange et al. first described the use of Doppler ultrasound to locate the subclavian artery during supraclavicular brachial plexus block [6]. By the mid-1990s, authors were reporting the use of real-time grey scale two-dimensional (2D) ultrasound images to guide needle placement during coeliac plexus and brachial plexus blocks [7,8].

To paraphrase the late Alon P. Winnie mentioned above, an in-depth knowledge of neuroanatomy is required to facilitate successful PNB. Although PNB is a simple concept, a number of important variables contribute to the challenge of successfully performing PNB. Individualised anatomical knowledge is perhaps the most important variable. It is widely accepted that human anatomy is not uniform. Differences in neuroanatomy exist both between individuals and also between the right and left sides of the same individual [9,10]. The introduction of ultrasonography to PNB has allowed a sufficiently detailed examination of anatomy at an individual basis, which permits the performance of accurate local anaesthetic deposition adjacent to nerves.

'Regional anaesthesia always works—provided you put the right dose of the right drug in the right place' [11]. Contemporary point-of-care ultrasound devices are capable of producing high-resolution images at real-time frame rates, which enables the anaesthesiologist to both identify relevant anatomical structures and guide needle and local anaesthetic placement. For those trained and proficient in ultrasound-guided PNB techniques, the greatest challenge currently faced relates to the identification of the needle tip location, and its relationship to the surface of the target nerve, immediately prior to local anaesthetic injection. This challenge may be thought of as two separate components: first, the epineurium is not well-visualised on ultrasound devices in clinical use; and second, ultrasound imaging renders a 2D image of 3D structures. Thanks to ultrasound and direct image guidance, the PNB needle has become a precision instrument that can accurately target nerves. Knowing when to stop forward needle advancement, however, is currently poorly understood.

The safety and success of PNB are determined principally by the location of the needle tip. Injection too far from the nerve risks block failure [12], and injection within the nerve risks nerve injury [13]. Axonal injury can be caused by both mechanical forces and cytotoxic effects of local anaesthetic injectate. It is known that intrafascicular injection causes significant histological abnormalities [14,15]. Contemporaneous estimates suggest that nerve injury following PNB occurs in 4–6 per 10,000 blocks [16,17]. Iatrogenic nerve injury can result in permanent sensory and motor dysfunction with neuropathic pain, resulting in catastrophic physical, psychological, social and economic consequences.

Technologies have been developed that may assist the clinician in clearly identifying the needle-to-nerve relationship prior to, and during, local anaesthetic injection. The following paragraphs will outline advances in technologies including ultrasound imaging, needle guidance assistance, needle design and needle tip sensing that may further refine PNB techniques and lead to improvements in the safety and efficacy of PNB.

Developments in ultrasound

> *'…if experience in other technological fields is to be used as a yardstick of the pace of development, the next 15 years will see an exponential increase in the quality of both 2D images and 3D ultrasound images'* [18].

Ultrasound displays

The quality of the ultrasound image has improved significantly over the recent past. Highly pixelated ultrasound images with poor feature discrimination have been replaced by high-quality images with clear boundary demarcation. Similar to the evolution in television from analogue to high definition (HD) images, a number of technical advances have facilitated this improvement. The resolution of ultrasound displays, as measured in the number of pixels displayed on the screen, has significantly changed. For example, common SVGA screens in the late 1990s were capable of displaying 800 × 600 pixels, while modern HD screens display 3840 × 2160 pixels and above. Contemporary displays, therefore, present more information per unit area and enhance the information presented to the clinician. HD tablet displays (in particular the Apple iPad(®) (Apple, Cupertino, CA) have been demonstrated to function equally as well as primary and secondary HD radiology displays without affecting diagnostic accuracy [19]. Modern displays are, therefore, capable of presenting image data with greater resolution than previously possible.

Ultrasound signal optimisation

The grey scale ultrasound image is generated when reflected sound waves return to the ultrasound probe and cause the piezoelectric elements to vibrate. This, in turn, generates an electrical signal, which is processed to form the image. Image quality is compromised by a number of variables such as speckle, noise and refractive shadows. Improvements in signal processing have resulted in better image quality [20]. Tissue harmonic imaging (THI) is one such commonplace advance in signal processing. By using the second (or higher) harmonic of the return ultrasound pulse frequency, THI can improve image quality by reducing signal artefact and clutter from superficial tissue [20]. THI is an important advance in musculoskeletal and neural imaging, given that most structures of interest to the regional anaesthesiologist exist in the first 2–3 cm beneath the skin. Harmonics can be adjusted manually to optimise the image on many devices including the GE's LOGIQ e (GE Healthcare, Wauwatosa, Wisconsin) as illustrated in Fig. 1.

Spatial compound imaging involves electronic steering of ultrasound beams from an array transducer. The same tissue is imaged multiple times using parallel beams oriented along different directions. The return signal from these parallel beams can be averaged together into a composite image. Spatial compound images have reduced levels of speckle, noise and acoustic artefacts with improved contrast and margin definition [21].

Speckle results in a granular interference with the grey scale image. It occurs as a result of the relative roughness of the reflector surface in relation to the sound wavelength. Reflected waves interact from independent scatters which generate noise that degrades image quality [22]. Upstream signal algorithmic filters have been developed, which lessen the impact of speckle on image quality. The advantages of such filters include clear reflector margins and artefact reduction, occasionally at the cost of losing image detail [20]. Adaptive speckle filters are often hidden behind the hardware of the ultrasound machine and invisible to the clinician. Clarity mode imaging on the SonixTouch GPS Ultrasound System (Ultrasonix Analogic Ultrasound, Richmond BC, Canada) is one example of an adaptive speckle filter, which can be manually selected during use (Fig. 2).

Ultrasound resolution

The resolution of the pulsed ultrasound signal is a further variable in the evolution of better ultrasound images. Axial resolution, defined as minimum distance between two reflectors lying parallel to ultrasound beam direction, is a function of the frequency of the ultrasound signal. Higher frequency

Fig. 1. Image of the control panel and keyboard of a GE's LOGIQ e (GE Healthcare, Wauwatosa, Wisconsin), with the Tissue Harmonic Imaging and Time Gain Compensation image optimisation functions highlighted.

Fig. 2. Image of the touch screen control panel of a SonixTouch GPS Ultrasound System (Ultrasonix Analogic Ultrasound, Richmond BC, Canada) with the speckle filter 'Clarity' function highlighted.

ultrasound signals have greater two point discrimination than lower frequency signals. Lateral resolution, defined as minimum distance between reflectors lying perpendicular to ultrasound beam direction, is a function of ultrasound beam width.

Beam width is, in turn, determined by high frequency, low wavelength ultrasound beams produced across a wide probe aperture [23].

Therefore, probes capable of producing high-frequency ultrasound >10 MHz, with a wide beam width, produce better images of reflectors, which lie in close proximity to one another. Information from modern high-frequency, high-resolution probes displayed on contemporary ultrasound displays has certainly improved the image quality [Fig. 3]. Note the somewhat hazy, heavily pixelated appearance of the ultrasound image, Fig. 3(a), in stark contrast to the sharp, well-defined tissue boundaries presented, in Fig. 3(b). These images were obtained using SonoSite Titan (Fig. 3) and SonoSite S-Nerve (Fig. 3) devices in 2006 and 2013, respectively (see Fig. 3).

Many commercially available point-of-care ultrasound devices incorporate sufficiently high-resolution probes (10–15 MHz) to identify reflectors with a small cross sectional area. This is important, given that the cross sectional area of superficial nerves is small. The normal median nerve at the wrist measures between 0.17 and 0.23 cm in diameter, with a cross sectional area between 9 and 11 mm^2 [24]. Individual fascial layers investing small peripheral nerves may measure only 1 mm or less in thickness. The challenge of accurately identifying the boundary between the outer surface of the target nerve(s) and their investing fascia remains problematic. Fig. 1(b) is an ultrasound image of the brachial plexus in the axilla. While the location of each nerve is clearly demarcated and annotated on the image; it is unclear as to where investing fascia ends and nerve begins.

Ultra-high frequency (UHF) ultrasound probes might provide a solution to this problem. UHF ultrasound produces ultrasound frequencies of up to 70 MHz and is capable of spatial resolution of up to 30 μm. Investigators have reported the ability to image superficial nerves (median nerve) and quantify fascicle number and size [25]. Investigators have also reported the potential utility of UHF ultrasound as a point-of-care diagnostic tool in hand trauma [26]. The image quality obtained using this technology allows clinicians to assess the integrity of nerve fascicles and vessel intima, and is likely to inform clinical decision making. UHF ultrasound certainly seems capable of producing high-resolution images with excellent two-point discrimination. Whether UHF ultrasound is feasible to guide paraneural needle and local anaesthetic placement is unknown.

3D/4D ultrasound

Three-dimensional ultrasound imaging may provide addition information to inform needle-to-nerve relationship during PNB performance. Multiplanar ultrasound probes acquire and process ultrasound data to produce a 3D representation of the target structure. The transformation of multiplanar 2D images into a 3D image requires some post-imaging computational processing. The term 4D imaging has been coined to represent real-time 3D ultrasound imaging [27]. Three-dimensional ultrasound guidance has been reported in continuous popliteal fossa sciatic block [28], axillary brachial plexus block [29] and radial nerve block [30]. Recently, Sala-Blanch et al. used 3D imaging to quantify the spread of paraneural local anaesthetic during popliteal fossa sciatic block, suggesting as little as 7 ml of local anaesthetic injectate may be sufficient to provide successful block [31].

Whether multiplanar probes and real-time 3D images will confer additional advantages to ultrasound-guided PNB is unknown. The appearance of 3D ultrasound images is very different to conventional 2D ultrasound. A new interpretive skillset is required to use 3D images in the performance of PNB. Clendenen et al. proposed a standardised approach to PNB and catheter placement using real-time 3D ultrasound guidance [32]. Further studies are required to determine whether 3D/4D US imaging can better identify the outer boundary of the nerve and help prevent inadvertent nerve puncture and intraneural injection.

Tissue elastography

Elastography in ultrasound is a measure of tissue elasticity and stiffness. A principal application of this feature to date has been in diagnostic ultrasound for cancer. Ultrasound is commonly used both as

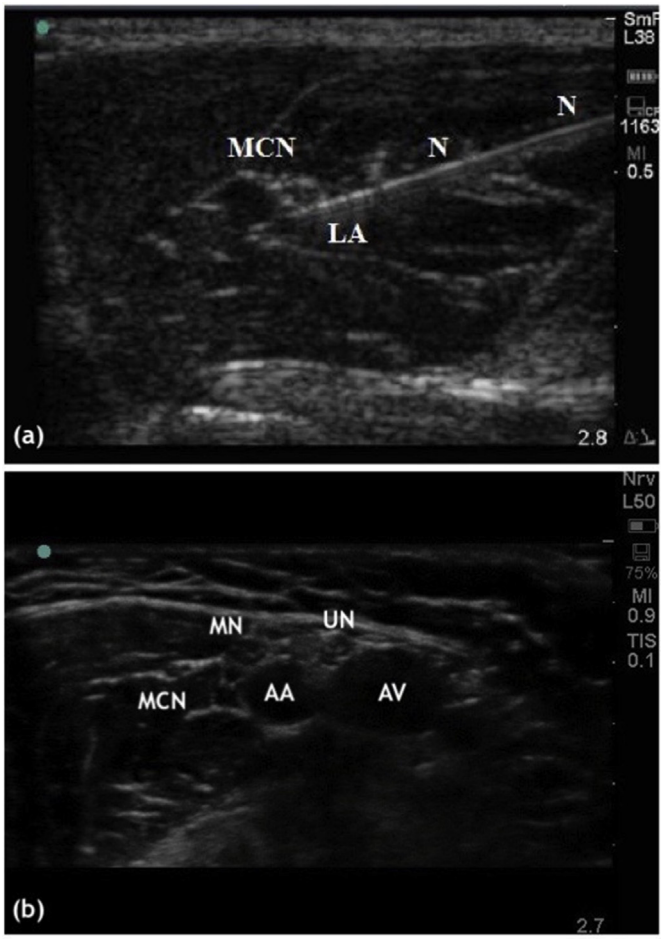

Fig. 3. (a) Ultrasound image of the musculocutaneous nerve following injection of local anaesthetic obtained using a SonoSite Titan unit (SonoSite®, Bothwell, WA, USA) with a 38 mm high-frequency (7–10 MHz) linear array transducer (L38). Image taken by the author in 2006. MCN = Musculocutaneous Nerve; N = Needle; LA = Local Anaesthetic. (b) Ultrasound image of the axillary brachial plexus obtained using a SonoSite S-Nerve unit (SonoSite®, Bothwell, WA, USA) with a 38 mm high-frequency (10–13 MHz) linear array transducer (L38). Image taken by the author in 2013. MCN = Musculocutaneous Nerve; MN = Median Nerve Complex; UN = Ulnar Nerve; AA = Axillary Artery; AV = Axillary Vein.

a diagnostic imaging tool and a modality to guide lesion biopsy in women with breast lesions. The stiffness of breast cancer and nodal disease differs from that of normal breast stroma. Elastography has been used as a supplemental tool to aid clinical decision making in the context of breast cancer [33,34]. Recently, investigators reported the use of elastography in regional anaesthesia. Munirama et al. used a combination of B-mode ultrasound and elastography to detect intraneural injection in soft-fix Thiel cadavers [35]. When compared with B-mode imaging alone, the 'fusion image' improved the ability of trainee anaesthesiologists to detect intraneural injection. Elastography may indeed have a role in detecting intraneural injection. The detection of intraneural injection may however not protect the vulnerable nerve from iatrogenic injury. Although identifying the misplaced needle tip and injectate is essential, the old adage of prevention being better than cure holds true.

Developments in needle technology

Needle in plane techniques requires the anaesthesiologist to carefully align the ultrasound probe and needle. Once aligned, the needle can be advanced visualising the needle tip and shaft at all times. This process is challenging and requires deliberate practice to master. Forward needle advancement without needle tip visualisation is one of the commonest errors performed by novices at ultrasound-guided PNB [36,37]. Should the needle migrate as little as 1 mm away from the centre of the ultrasound probe, it will fail to reflect the ultrasound beam and not be visualised. Industry has developed technology to both assist in visualisation of the needle and to replace needle visualisation with augmented guidance systems.

Ultrasound optimised needles have been in existence for some time. Various techniques have been employed by competing manufacturers to alter the surface characteristics of the needle, thereby creating nonlinear ultrasound reflectors that enhance needle tip and shaft visibility. Pajunk for instance has designed a needle surface with embossed pyramidal reflectors on the SonoPlex Nanoline needle (Pajunk, Geisingen, Germany), while the B-Braun Stimuplex Ultra 360 (B. Braun Melsungen, Melsungen, Germany) has X-shaped reflectors arranged on the tip and shaft (Fig. 4). Other needle manufacturers have altered the composition of the passivation layer of needle insulation to render similar ultrasound effects. Non-linear reflectors on the needle surface produce characteristic signals that facilitate visual identification of the needle. When compared to standard PNB needles, echogenic needles have superior visibility irrespective of operator experience or needle insertion angle [38].

Needle guidance

Better needle visibility still requires the needle to be correctly aligned with the ultrasound beam. Articulated needle guides have been described and validated that correctly orientate the needle to probe [39,40]. These guides maintain the needle in the plane of the ultrasound beam and improve

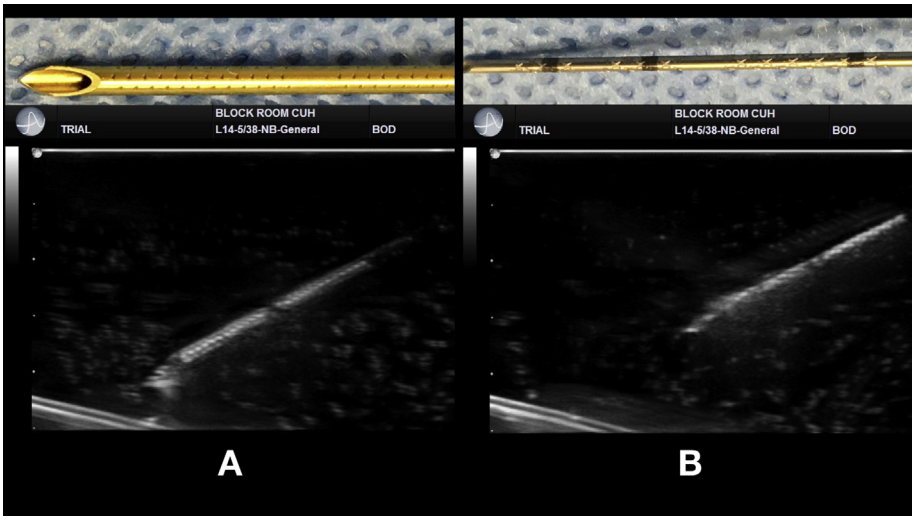

Fig. 4. (A) Image of Pajunk SonoLong NanoLine 19G ultrasound optimised needle (Pajunk, Geisingen, Germany) above an ultrasound image obtained in a water bath. Note the embossed 'Cornerstone ®' pattern on the needle and the resultant ultrasonographic enhancement of needle shaft. (B) Image of B. Braun's Stimuplex Ultra 360 A50 (B. Braun Melsungen, Melsungen, Germany) above an ultrasound image obtained in a water bath. Note the X-shaped grooves on the needle shaft and the resultant ultrasonographic enhancement of the needle shaft.

needle visualisation. They are however a little bulky and cumbersome, and may restrict the freehand movement of the block needle. The role of needle guides in PNB requires additional evaluation.

Needle guidance systems have been developed, which provide user feedback as to needle tip position without the need to directly visualise the needle. Magnetic ultrasound guidance creates an augmented reality with live needle tracking and prediction of needle trajectory. Several systems have been evaluated for both regional anaesthesia and vascular access. The SonixGPS system (Ultrasonix Analogic Ultrasound, Richmond BC, Canada) uses a magnetic field generator and sensors on the needle and ultrasound probe (Fig. 5). A real-time overlay of needle trajectory and needle tip location is displayed on the ultrasound image [41]. A prototype device, Venue 50 Ultrasound prototype with L12n-SC transducer (GE Healthcare, Wauwatosa, Wisconsin), has similar needle tracking functionality with the magnetic tracking technology embedded in the ultrasound probe and needle. In comparative studies, needle guidance technology has improved first pass success in both simulated regional anaesthesia and vascular access techniques [42–44]. Although magnetic guidance systems may assist in moving the needle towards a target, this technology fails to image the needle through its path from skin to target. The user may misinterpret the technology as a safe means to guide a needle from skin surface to target nerve. Needles advanced without visualisation of needle tip and shaft may inadvertently injure structures (vessels, nerves, pleura etc) that are outside the beam of the ultrasound and not visualised. It is unknown if magnetic guidance will ultimately improve the accuracy of needle placement during

Fig. 5. SonixTouch GPS system, utrasonix analogic ultrasound, richmond BC, Canada.

PNB. Whether needle guidance systems will enhance the safety of ultrasound guided PNB is of even greater uncertainty.

Robotic assistant devices are now commonplace during minimal access surgery. Robotic assistance has been reported in hysterectomy, prostatectomy, nephrectomy colon resection, liver resection and lung resection surgery. Robotic assistance is thought to improve patient outcome, particularly in terms of pain, postoperative recovery and blood transfusion requirements, when compared to standard laparoscopic and open surgery. The evidence to support this assertion is somewhat in doubt, particularly in prostatectomy [45]. Robotic assistance has been reported in bench models of ultrasound-guided PNB in which robots advanced the needle towards a target [46,47]. These manuscripts report the feasibility of needle advancement in a bench simulation of ultrasound guided PNB. There are no data to validate the use of robotics within the context of clinical PNB performance, and none to suggest better definition of needle nerve relationship. Given the prohibitive costs associated with robotic assistance, it is unlikely that regional anaesthesiologists will be replaced by robotic devices in the near future.

Sensing needles

Injectate pressure monitoring

The intraneural space consists of neural tissue embedded with connective tissue. This is a variably distensible space. Intraneural, but especially intrafascicular administration of local anaesthetic solution, will result in a rise in pressure within the nerve [48]. Injection pressures >20 psi have been shown to cause neurological injury in animals [49]. Injection pressures of 15 psi have been associated with needle to nerve contact during interscalene block [50]. Anaesthesiologists are poorly able to appreciate injection pressures thought to be unsafe [51]. For some time, in-line pressure manometers such as B-smart (B-Smart, B. Braun Medical, Bethlehem, PA, USA) have been used to determine the pressure of injectate leaving the syringe. Recently, a novel optical pressure transducer has been integrated into the needle tip and has questioned the validity of inline pressure monitoring [52]. Using this novel technology, investigators have validated the ability the sensorised needle to detect intraneural injection [53]. Furthermore, the effects of injection rate on both inline pressure monitoring and needle tip pressure monitoring have been characterised and compared. Investigators suggest that inline pressure monitoring does not accurately reflect pressure and flow dynamics at the needle tip [54]. If injectate pressure is to be used as a reliable means to detect, and more importantly prevent intraneural injection, perhaps optical needle tip pressure monitoring will provide more accurate, real-time user feedback. It must be remembered however that high injectate pressure may be related to other factors such as needle outlet obstruction, tissue compression and injection into poorly distensible structures such as tendon. The non-specificity of injectate pressure might negatively influence operator behaviour and impact block performance. Additional validation is warranted to accurately define the role of pressure monitoring in PNB.

Bioimpedance

Ohms law dictates that the current in a circuit measured in amperes (A) is equal to the voltage measured in volts (V) divided by the resistance measured in ohms (R) giving the formula $A = V/R$. Every material will impede (resist) electrical current to a greater or lesser extent. When alternating current is applied across two or more electrodes to biological tissue, the resistance to current flow between cathode and anode is referred to as bioimpedance. The conductivity of biological materials is electrolytic and principally based on Sodium (Na^+) and Chloride (Cl^-) ions. Changes in ion concentration lead to changes in bioimpedance. Cell membranes separate intracellular from extracellular fluid, which creates two electrolytic systems. This separation of intracellular from extracellular fluid confers capacitor (energy storing) characteristics on living cells [55]. Cell membranes have low conductivity; therefore, cellular density (number per unit area) influences bioimpedance [56,57]. Cell size, orientation and membrane thickness also influence bioimpedance, thus enhancing the ability to discriminate between tissues using bioimpedance [58]. Some tissues are very good conductors of electricity,

while others are poor conductors. Bone has a measured resistivity of >40 Ω and muscle has a resistivity of 2–4 Ω at 10 kHz [59].

Kalvoy et al. successfully designed and validated an invasive dual electrode array mounted on a hypodermic needle to confirm needle position within tissues such as muscle, fat, liver etc. [60]. Furthering this logic, Tsui et al. evaluated the role of impedance measurement in detecting intraneural needle placement in a porcine model of ultrasound-guided PNB. Using the impedance output on the Stimuplex HNS 12 (B. Braun Medical, Bethlehem, PA), a difference in bioimpedance between extraneural and intraneural needle placement was noted [61]. Kalvoy and co-investigators have since validated their technology to identify both intraneural needle placement and CSF during ultrasound-guided PNB and lumbar puncture, respectively [62,63].

Optical reflectance spectroscopy

Optical fibres have been used to augment needles and differentiate between tissue types encountered at the needle tip. Light of varying wavelength can be transmitted along optical fibres while sensing fibres in the device detect reflected and scattered light. The optical properties of the tissue(s) can be quantified, forming the basis of tissue identification [64,65]. The optical properties of biological tissues are determined by chromophores such as haemoglobin; myoglobin, lipid and water of different composition (fat, muscle and nerve) absorb and reflect light differently [64]. To date, applications of this technology focussed on cancer diagnostics in breast, prostate and ovary [66–68]. Recently, Balthazar et al. reported the use of optical spectroscopy to identify both vascular puncture and nerve detection during nerve blocks [69,70].

Sensorised needles may provide additional user information and help detect the needle to nerve contact and intraneural needle placement. Each of the technologies outlined in the above paragraphs is in very early phase development. Whether any technological advance is sufficiently sensitive and specific to truly characterise the needle–nerve relationship prior to local anaesthetic injection remains to be seen.

Conclusion

PNB techniques have evolved beyond recognition. Our understanding of individualised human anatomy has been significantly advanced by modern point of care ultrasound devices. Multiple technologies have been developed to enhance needle visibility, guide the needle towards the nerve(s) and detect inadvertent intraneural needle placement. It is likely that many of the technologies outlined in the above chapters will further enhance the safety and efficacy of PNB into the 21st century.

Practice points

- The interaction between the needle and the nerve at the moment of injection is critical to both block success and safety;
- Technology has advanced to permit the acquisition of high-resolution and HD ultrasound images;
- UHF and 3D/4D ultrasound may have a role to play in improving block safety and efficacy;
- Needles optimised for ultrasound guidance perform better at steep angles and usually have visible markings to aid in needle tip identification; they are equally invisible to standard needles if not placed within the confines of the ultrasound beam;
- Needle guidance systems may assist the anaesthesiologist in moving the needle from skin towards the target, with some caveats about adopting out of plane techniques;
- Sensorised needles using pressure monitoring, bioimpedance or optical spectroscopy may help detect needle to nerve contact and avoid intraneural local anaesthetic injection;

Research agenda

- Nerve injury is rare. Given the complexity and expense of clinical research, it is unlikely that any developed technology will ever be shown to lessen the occurrence of nerve injury;
- Technologies that focus on better defining the nerve surface using imaging or image enhancement media may better define the epineurium;
- The integration of needle guidance systems into clinical practice must be accompanied by robust training and measures of proficiency in their use;
- Sensorised needle technology is exciting but requires additional validation.

References

[1] Winnie AP, Buckheoj P, Hoakansson L. Plexus anesthesia: perivascular techniques of brachial plexus block, Revis Edition. Philadelphia: Saunders; 1994. p. 9.
[2] Koller C. On the use of cocaine for producing anaesthesia on the eye. Lancet 1884;2:990–2.
[3] Halsted WS. Practical comments on the use and abuse of cocaine; suggested by its invariably successful employment in more than a thousand minor surgical operations. N Y Med J 1885;42:294–5.
[4] Pearson RB. Nerve block in rehabilitation: a technique of needle localization. Arch Phys Med Rehabil 1955;26:631–3.
[5] Greenblatt GM, Denson JS. Needle nerve stimulator locator. Nerve blocks with a new instrument for locating nerves. Anesth Analg 1962;41:599–602.
[6] La Grange P, Foster PA, Pretorius LK. Application of the Doppler ultrasound bloodflow detector in supraclavicular brachial plexus block. Br J Anesth 1978;50:965–7.
[7] Kirvelä O, Svedström E, Lundbom N. Ultrasonic guidance of lumbar sympathetic and celiac plexus block: a new technique. Reg Anesth 1992;17:43–6.
[8] Kapral S, Krafft P, Eibenberger K, et al. Ultrasound-guided supraclavicular approach for regional anesthesia of the brachial plexus. Anesth Analg 1994;78:507–13.
[9] Royse CE, Sha S, Soeding PF, et al. Anatomical study of the brachial plexus using surface ultrasound. Anaesth Intensive Care 2006;34:203–10.
[10] Soeding P, Eizenberg N. Review article: anatomical considerations for ultrasound guidance for regional anesthesia of the neck and upper limb. Can J Anaesth 2009 Jul;56(7):518–33.
[11] Denny NM, Harrop-Griffiths W. Location, location, location! Ultrasound imaging in regional anaesthesia. Br J Anaesth 2005;94:1–3.
*[12] Albrecht E, Kirkham KR, Taffe P, et al. The maximum effective needle-to-nerve distance for ultrasound-guided interscalene block: an exploratory study. Reg Anesth Pain Med 2014;39:56–60.
[13] Cohen JM, Gray AT. Functional deficits after intraneural injection during interscalene block. Reg Anesth Pain Med 2010; 35:397–9.
[14] Whitlock EL, Brenner MJ, Fox IK, et al. Ropivacaine-induced peripheral nerve injection injury in the rodent model. Anesth Analgesia 2010;111:214–20.
[15] Lupu CM, Kiehl TR, Chan VW, et al. Nerve expansion seen on ultrasound predicts histologic but not functional nerve injury after intraneural injection in pigs. Reg Anesth Pain Med 2010;35:132–9.
[16] Orebaugh SL, Williams BA, Vallejo M, et al. Adverse outcomes associated with stimulator-based peripheral nerve blocks with versus without ultrasound visualization. Region Anesth Pain Med 2009;34:251–5.
*[17] Barrington MJ, Watts SA, Gledhill SR, et al. Preliminary results of the australasian regional anaesthesia collaboration: a prospective audit of more than 7000 peripheral nerve and plexus blocks for neurologic and other complications. Region Anesth Pain Med 2009;34:534–41.
*[18] Marhofer P, Harrop-Griffiths W, Kettner SC, et al. Fifteen years of ultrasound guidance in regional anaesthesia: Part 1. Br J Anaesth 2010;104:538–46.
[19] Caffery LJ, Armfield NR, Smith AC. Radiological interpretation of images displayed on tablet computers: a systematic review. Br J Radiol 2015;88:2015019.
*[20] Hangiandreou NJ. AAPM/RSNA physics tutorial for residents: topics in US. Radiographics 2003;23:1019–33.
[21] Entrekin RR, Porter BA, Sillesen HH, et al. Real-time spatial compound imaging: application to breast, vascular, and musculoskeletal ultrasound. Semin Ultrasound CT MRI 2001;22:50–64.
[22] Zhang J, Lin G, Wu L, et al. Speckle filtering of medical ultrasonic images using wavelet and guided filter. Ultrasonics 2016; 65:177–93.
[23] Ng A, Swanevelder J. Resolution in ultrasound imaging. Cont Educ Anaesth Crit Care Pain 2011;11:186–92.
[24] Sucher BM. Ultrasound imaging of the carpal tunnel during median nerve compression. Curr Rev Musculoskelet Med 2009;2:134–46.
[25] Cartwright MS, Baute V, Caress JB, et al. Ultrahigh-frequency ultrasound of fascicles in the median nerve at the wrist. Muscle Nerve 2017;56:819–22.
[26] Viviano SL, Chandler LK, Keith JD. Ultrahigh frequency ultrasound imaging of the hand: a new diagnostic tool for hand surgery. Hand 2018;13:720–5.
*[27] French JLH, Raine-Fenning NJ, Hardman JG, et al. Pitfalls of ultrasound guided vascular access: the use of three/four-dimensional ultrasound. Anaesthesia 2008;63:806–13.

[28] Feinglass NG, Clendenen SR, Torp KD, et al. Real-time three dimensional ultrasound for continuous popliteal blockade: a case report and image description. Anesth Analg 2007;105:272–4.
[29] Clendenen SR, Riutort K, Ladlie BL, et al. Real-time three dimensional ultrasound-assisted axillary plexus block defines soft tissue planes. Anesth Analg 2009;108:1347–50.
[30] Foxall GL, Hardman JG, Bedforth NM. Three dimensional, multiplanar, ultrasound-guided, radial nerve block. Reg Anesth Pain Med 2007;32:516–21.
[31] Sala-Blanch X, Franco J, Bergé R, et al. Rev Esp Anestesiol Reanim 2017;64:125–30.
*[32] Clendenen NJ, Robards CB, Clendenen SR. A standardized method for 4D ultrasound-guided peripheral nerve blockade and catheter placement. Biomed Res Int 2014;2014:920538.
[33] Cosgrove DO, Berg WA, Doré CJ, et al. Shear wave elastography for breast masses is highly reproducible. Eur Radiol 2012; 22:1023–32.
[34] Bae SJ, Park JT, Park AY, et al. Ex vivo shear-wave elastography of axillary lymph nodes to predict nodal metastasis in patients with primary breast cancer. J Breast Cancer 2018;21:190–6.
[35] Munirama S, Zealley K, Schwab A, et al. Trainee anaesthetist diagnosis of intraneural injection-a study comparing B-mode ultrasound with the fusion of B-mode and elastography in the soft embalmed Thiel cadaver model. Br J Anaesth 2016;117: 792–800.
*[36] Sites BD, Gallagher JD, Cravero J, et al. The learning curve associated with a simulated ultrasound-guided interventional task by inexperienced anesthesia residents. Reg Anesth Pain Med 2004;29:544–8.
*[37] Barrington MJ, Viero LP, Kluger R, et al. Determining the learning curve for acquiring core sonographic skills for ultrasound-guided axillary brachial plexus block. Reg Anesth Pain Med 2016;4:667–70.
[38] Hocking G, Mitchell CH. Optimizing the safety and practice of ultrasound-guided regional anesthesia: the role of echogenic technology. Curr Opin Anaesthesiol 2012;25:603–9.
[39] Gupta RK, Lane J, Allen B, et al. Improving needle visualization by novice residents during an in-plane ultrasound nerve block simulation using an in-plane multiangle needle guide. Pain Med 2013;14:1600–7.
[40] Bigeleisen P. Design and production of an articulating needle guide for ultrasound-guided needle block manufactured with a three-dimensional printer: technical communication. A&A Pract 2017;8:272–5.
[41] Tang R, Sawka A, Vaghadia H, et al. SonixgpsTM needle tracking system for out-of-plane brachial plexus block in human cadavers. Acta Anaesthesiol Scand 2013;57:398–9.
[42] Swenson JD, Klingler KR, Pace NL, et al. Evaluation of a new needle guidance system for ultrasound: results of a prospective, randomized, blinded study. Reg Anesth Pain Med 2016;41:356–61.
[43] Johnson AN, Peiffer JS, Halmann N, et al. Ultrasound-guided needle technique accuracy: prospective comparison of passive magnetic tracking versus unassisted echogenic needle localization. Reg Anesth Pain Med 2017;42:223–32.
[44] Scholten HJ, Pourtaherian A, Mihajlovic N, et al. Improving needle tip identification during ultrasound-guided procedures in anaesthetic practice. Anaesthesia 2017;72:889–904.
[45] Ilic D, Evans SM, Allan CA, et al. Laparoscopic and robot-assisted vs open radical prostatectomy for the treatment of localized prostate cancer: a Cochrane systematic review. BJU Int 2018;121:845–53.
[46] Tighe PJ, Badiyan SJ, Luria I, et al. Technical communication: robot-assisted regional anesthesia: a simulated demonstration. Anesth Analg 2010;111:813–6.
[47] Morse J, Terrasini N, Wehbe M, et al. Comparison of success rates, learning curves, and inter-subject performance variability of robot-assisted and manual ultrasound-guided nerve block needle guidance in simulation. Br J Anaesth 2014; 112:1092–7.
[48] Vermeylen K, Hermans M, Soetens F, et al. Opening injection pressure Is higher in intraneural compared with perineural injections using simulated nerve blocks of the lower limb in fresh human cadavers. Reg Anesth Pain Med 2017;42:362–7.
*[49] Hadzic A, Dilberovic F, Shah S, et al. Combination of intraneural injection and high injection pressure leads to fascicular injury and neurologic deficits in dogs. Reg Anesth Pain Med 2004;29:417–23.
[50] Gadsden JC, Choi JJ, Lin E, et al. Opening injection pressure consistently detects needle–nerve contact during ultrasound-guided interscalene brachial plexus block. Anesthesiology 2014;120:1246–53.
[51] Claudio R, Hadzic A, Shih H, et al. Injection pressures by anesthesiologists during simulated peripheral nerve block. Reg Anesth Pain Med 2004;29:201–5.
[52] Quadri C, Saporito A, Capdevila X. Real-time continuous monitoring of injection pressure at the needle tip for peripheral nerve blocks: description of a new method. Anaesthesia 2018;73:187–94.
[53] Saporito A, Quadri C, Capdevila X. The ability of a real-time injection pressure monitoring system to discriminate between perineural and intraneural injection of the sciatic nerve in fresh cadavers. Anaesthesia 2018;73:1118–22.
[54] Saporito A, Quadri C, Kloth N, et al. The effect of rate of injection on injection pressure profiles measured using in-line and needle-tip sensors: an in-vitro study. Anaesthesia 2019;74:64–8.
[55] Gitter AH, Fromm M, Schulzke J-D. Impedance analysis for the determination of epithelial and subepithelial resistance in intestinal tissues. J Biochem Biophys Meth 1998;37:35–46.
[56] Dean DA, Ramanathan T, Machado D, et al. Electrical impedance spectroscopy study of biological tissues. J Electrost 2008; 66:165–77.
[57] Miklavcic D, Pavselj N, Hart FX. Electric properties of tissues. Wiley encyclopedia of biomedical engineering. Hoboken, NJ: John Wiley & Sons, Inc.; 2006.
[58] Bayford RH. Bioimpedance tomography (electrical impedance tomography). Annu Rev Biomed Eng 2006;8:63–91.
[59] Brown BH. Electrical impedance tomography (EIT): a review. J Med Eng Technol 2003;27:97–108.
[60] Kalvøy H, Frich L, Grimnes S, et al. Impedance-based tissue discrimination for needle guidance. Physiol Meas 2009;30: 129.
*[61] Tsui BC, Pillay JJ, Chu KT, et al. Electrical impedance to distinguish intraneural from extraneural needle placement in porcine nerves during direct exposure and ultrasound guidance. Anesthesiology 2008;109:479–83.
[62] Kalvøy H, Sauter AR. Detection of intraneural needle-placement with multiple frequency bioimpedance monitoring: a novel method. J Clin Monit Comput 2016;30:185–92.

[63] Halonen S, Annala K, Kari J, et al. Detection of spine structures with Bioimpedance Probe (BIP) Needle in clinical lumbar punctures. J Clin Monit Comput 2017;31:1065–72.
[64] Ting CK, Tsou MY, Chen PT, et al. A new technique to assist epidural needle placement: fiberoptic-guided insertion using two wavelengths. Anesthesiology 2010;112:1128–35. 72.
[65] Doornbos RMP, Lang R, Aalders MC, et al. The determination of in vivo human tissue optical properties and absolute chromophore concentrations using spatially resolved steady-state diffuse reflectance spectroscopy. Phys Med Biol 1999; 44:967.
[66] Colak SB, Van Der Mark MB, Hooft GWt, et al. Clinical optical tomography and NIR spectroscopy for breast cancer detection. IEEE J Sel Top Quan Electron 1999;5:1143–58.
[67] Sharma V, Kashyap D, Mathker A, et al. Optical reflectance spectroscopy for detection of human prostate cancer. Conf Proc IEEE Eng Med Biol Soc 2009;2009:118–21.
[68] Utzinger U, Brewer M, Silva E, et al. Reflectance spectroscopy for in vivo characterization of ovarian tissue. Lasers Surg Med 2001;28:56–66.
[69] Balthasar A, Desjardins AE, van der Voort M, et al. Optical detection of vascular penetration during nerve blocks: an in vivo human study. Reg Anesth Pain Med 2012;37:3–7.
[70] Balthasar A, Desjardins AE, van der Voort M, et al. Optical detection of peripheral nerves: an in vivo human study. Reg Anesth Pain Med 2012;37:277–82.