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Review Article

The role of peripheral nerve stimulation in the era of ultrasound-guided regional anaesthesia

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Summary
With the widespread use of ultrasound for localising nerves during peripheral nerve blockade, the value of electrical nerve stimulation of evoked motor responses has been questioned. Studies continue to show that, compared with nerve stimulation, ultrasound guidance alone leads to: significantly improved block success; decreased need for rescue analgesia; decreased procedural pain; and lower rates of vascular puncture. Nerve stimulation combined with ultrasound does also not appear to improve block success rates, apart from those blocks where the nerves are challenging to view, such as the obturator nerve. The role of nerve stimulation has changed in the last 15 years from a technique to locate nerves to that of an adjunct to ultrasound. Nerve stimulation can serve as a monitor against needle-nerve contact and may be useful in avoiding nerves that are in the needle trajectory during specific ultrasound guided techniques. Nerve stimulation is also a useful adjunct in teaching novices ultrasound-guided regional anaesthesia, especially when the position and or appearance of nerves may be variable. In this review, the changing role of nerve stimulation in contemporary regional anaesthetic practice is presented and discussed.

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Introduction
Safe and successful nerve blockade is predicated on placing local anaesthetic close enough to the nerve or plexus that it can reach the nerve fibres, but not so close as to cause mechanical injury from needle-nerve contact. The fact that peripheral nerve blockade success rates have never been perfect suggests that, to a degree, finding the 'sweet spot' can be elusive, and that we can be imprecise in our efforts at nerve localisation.

Electrical stimulation of peripheral nerves during nerve blockade became commonplace in the 1970s as a means to locate peripheral nerves and plexi with greater precision [1, 2]. Before the introduction of nerve stimulation, clinicians made use of anatomical landmarks, haptic feedback (pops, clicks and loss of resistance) and/or patient-reported paraesthesia to infer needle position relative to the target nerve. By evoking a motor response of the muscle(s) associated with that nerve (or trunk, division, cord, etc.), clinicians could now make a more quantitative inference of the needle/nerve relationship by advancing the needle until the response was present below a certain threshold current intensity (e.g. 0.5 mA). This innovation helped to reduce block failure rates compared with landmark/paraesthesia techniques and made regional anaesthesia less of an 'art' by ushering in an era of peripheral nerve blockade that was both more objective and scientific [3, 4]. The nerve stimulation era lasted for several decades while the technology became the basis of modern regional anaesthetic practice.

With the widespread adoption of ultrasound guidance in the 21st century, the needle could now be observed approaching the target in real time. Studies comparing ultrasound with non-ultrasound block techniques have since demonstrated overall improved block safety and effectiveness with ultrasound [5–7], as well as mediocre sensitivity of stimulation for nerve localisation [8, 9]. Not surprisingly, some have questioned whether continuing to seek an evoked motor response of the nerve still holds value when all the information needed is right before our eyes. This may be especially relevant as ultrasound technology becomes cheaper and more widely available to anaesthetists around the globe. The purpose of this narrative review is to provide an overview of the advantages and drawbacks of electrical nerve stimulation, and define the role of nerve stimulation in contemporary regional anaesthetic practice.

Evoked motor response to electrical stimulation: theory and challenges

The idea of stimulating a nerve with a small electrical current to provoke a specific motor response is a simple and attractive one. Compound nerves contain motor fibres that can be directly depolarised using electrical current applied to the nerve, resulting in contraction of the corresponding muscles. In regional anaesthetic practice, this is typically done using an insulated needle in order to concentrate the current density at the tip of the needle. The higher the current intensity (mA), the larger the 'sphere' of high-density current present at the needle tip, and the greater the likelihood of depolarisation of an adjacent nerve [10]. The current intensity required to elicit a motor response from a nerve, according to Coulomb's Law, is inversely proportional to the square of the distance to the nerve. Theoretically, as the operator advances the stimulating needle towards the nerve, the current intensity needed to yield a motor response diminishes exponentially. In a practical sense, clinicians make assumptions about the distance from the needle tip to the nerve based on the intensity of the motor response, as well as other haptic and visual feedback.

Traditional teaching was that to locate a nerve efficiently and precisely, a clinician should start with a high current intensity (e.g. > 1.0 mA) and advance in the likely direction of the nerve based on anatomical landmarks. When a motor response is obtained, the current intensity is gradually reduced until the motor response diminishes or disappears. The needle is then advanced until the motor response returns or is amplified. The current intensity is reduced again, the needle advanced and this procedure is repeated until a sustained motor response is obtained at an acceptable threshold current intensity, usually between 0.2 and 0.5 mA. This threshold current has traditionally been thought to be associated with a sufficiently small distance from the nerve so that injected local anaesthetic would result in an effective block [11].

While attractive as a model, there are several limitations to this simplified description of evoked motor stimulation. First, the current always follows the path of least electrical resistance, and may be channelled asymmetrically in a way that interferes with the interpretation of the motor response [12]. For example, various tissue elements (fascia, water, fat, etc.) surrounding the needle tip may direct current away from the nerve before returning to the skin anode. This may result in a false negative result, where no motor response is obtained despite the needle being quite close or even, as confirmed by provoking paraesthesia, contacting the nerve [9, 13]. Similarly, Perlas et al. demonstrated that, with a current intensity of 0.5 mA or less, needles contacting branches of the axillary brachial plexus (as confirmed with ultrasound) failed to produce a motor response in 25% of cases [8]. Moreover, animal models have shown that, even with current intensities greater than 1.0 mA, a needle tip can be inserted within the nerve and fail to produce a motor response [14, 15]. The explanation for this surprising finding is multifactorial, and likely relates to the spatial composition of sensory and motor fibres within the nerve, the relative electrical conductance and resistance of the neural connective tissue, and evidence that nerve hyperpolarisation and conduction block can occur with high current intensity [16].

Second, false positives can occur. Despite an acceptable evoked motor response, the needle tip (and subsequently, the deposited local anaesthetic) may be located within an adjacent muscle or one or more fascial planes away from the neural target, resulting in a failed block [17]. It appears that some connective tissue layers may permit electrical current to travel through, while preventing the local anaesthetic solution from reaching the nerves [18].

Third, local anaesthetic solutions conduct electrical currents with ease. Once the administration of local anaesthetic has commenced, the evoked motor response ceases due to conductance of the current to locations other than the nerve [10]. This limits the role of nerve stimulation to the initial part of the block procedure, before the injection of local anaesthetic. Any subsequent need for stimulation (in the same area) is difficult or impossible after local anaesthetic is administered. The injection of dextrose 5% or sterile water permits the continued stimulation of an evoked motor response, as these solutions are non-conductive [10].

Nerve stimulation vs. ultrasound for nerve localisation

Once ultrasound guidance became popular in the regional anaesthetic community, comparative studies against nerve stimulation naturally followed. A 2009 meta-analysis by Abrahams et al. comprising 13 studies comparing ultrasound alone vs. nerve stimulation alone demonstrated: increased block success rate; decreased block procedure time; faster block onset; and longer block duration [19]. Ultrasound also conferred an 84% relative risk reduction for vascular puncture compared with nerve stimulation. More recently, a similar meta-analysis of 23 trials (2125 participants) showed that nerve localisation with ultrasound (as compared with electrical stimulation) significantly increased block success rate (91.8% vs. 82.8%, respectively) and decreased pain during the procedure as well as the need for rescue analgesia or anaesthesia [20]. Vascular puncture rates were significantly reduced with the use of ultrasound in this analysis. A third meta-analysis of continuous perineural catheter techniques using ultrasound vs. nerve stimulation found similar results, with ultrasound improving overall block success and reducing vascular puncture rates [21]. These three analyses highlight the invaluable role of ultrasound in identifying the target nerve structures as well as avoiding accidental injury to neighbouring blood vessels. Guiding a needle precisely using visual feedback holds several advantages over a (proven insensitive) method that relies on surface landmarks and knowledge of underlying anatomy.

Nonetheless, critics of some of these individual comparative studies have pointed out that block success rates for the nerve stimulation groups seem inordinately low (60–75%) compared with what might be expected from experienced anaesthetists [22–24]. The reasons for this are unclear, but may relate to the choice of motor response and/or the accepted minimum threshold current used studies [24].

The studies in these analyses all posed a comparative question: whether ultrasound or nerve stimulation is better than the other. A different question is whether the addition of nerve stimulation to ultrasound guidance offers any advantage for nerve block procedures. Results appear to be consistent across femoral nerve block [25, 26], interscalene brachial plexus block [27], infraclavicular brachial plexus block [28], and popliteal sciatic nerve block [29] techniques, as data show no difference in block success and/or pain scores. This suggests that for nerve targets that are relatively easy to view, nerve stimulation may not confer an additional advantage when used with ultrasound guidance.

However, deep nerves or those that are difficult to view may benefit from the concomitant use of nerve stimulation as a confirmation of needle tip placement. Two studies compared obturator nerve blocks performed using ultrasound alone with ultrasound and nerve stimulation [30, 31]. Both found higher success rates when a motor response was sought using stimulation. This finding is not surprising, given that viewing the anterior and posterior branches of the obturator nerves in the adductor muscle planes is frequently challenging. Similarly, parasacral sciatic, subgluteal sciatic and posterior lumbar plexus blockade may benefit from the use of nerve stimulation [32], as the ultrasound image of the nerve(s) in both examples may not be ideal, especially in obese patients. Our institutional experience is to routinely use combined ultrasound and nerve stimulation for both block techniques, for the additional confirmatory data.

Ultrasonography to locate nerves during block procedures is superior to nerve stimulation alone, and has become the de facto standard in many places for that task. Moreover, using nerve stimulation as a supplement to ultrasound-guided techniques does not appear to add value to success rates, outside of obturator nerve block. However, this does not necessarily mean that nerve stimulators are now obsolete.

Nerve stimulation as a monitor for nerve block safety

Nerve injury following regional anaesthesia continues to occur despite technological advances, and nearly 50 years of research on this topic can be distilled into four points. First, needle entry into the nerve fascicle is likely to cause direct or indirect injury to axons and other vulnerable structures. Second, it is difficult to avoid every fascicle if a needle is placed inside a nerve. Third, inflammation occurs because of needle-nerve contact, let alone nerve penetration. Fourth, nerve blockade is safe and effective when local anaesthetic is placed outside the nerve and needle-nerve contact does not occur [33–36].

Ultrasound is invaluable, but like many other tools, is highly user-dependent. Its effective and safe use requires extensive knowledge of anatomy and sonoanatomy, as well as good technical skills. Even in skilled hands, the needle tip may not always be visible all the time. Moreover, the success rate of expert anaesthetists to correctly interpret intra- vs. extra-neural needle positions using ultrasound during sciatic nerve blockade is less than 80% [37]. Ultrasound is good in human hands, but is undoubtedly not without its own problems.

While electrical stimulation has been shown to be insensitive for nerve localisation [8, 9], it may be useful as a second layer of protection when used in conjunction with ultrasound. Animal and human data suggest that if a motor response is obtained at or below a threshold of 0.2 mA, the needle tip is highly likely to be contacting the nerve or is, in fact, intra-neural [11, 14, 38, 39]. Put another way, it is unlikely to elicit a motor response at that current intensity when the needle is safely outside the nerve. As such, nerve stimulation is a highly specific monitor for needle-nerve contact. This provides the rationale for the concomitant use of nerve stimulation alongside ultrasound in contemporary practice: rather than use it to find nerves, it may best be used to warn of accidental needle-nerve contact that may not be recognised by ultrasound. While < 0.2 mA is the threshold that seems to most accurately discriminate needle-nerve contact vs. extra-neural needle position, many anaesthetists feel more comfortable setting the current intensity higher (e.g. 0.5 mA or greater) with the intention of allowing even earlier warning of impending needle-nerve contact [11, 40]. Our practice is to set the nerve stimulator at a starting current intensity of 0.5-1.0 mA, with a pulse width of 0.1 msec, and advance the needle under ultrasound guidance towards the target (Fig. 1). If the needle can be placed adjacent to the nerve while avoiding contact, and a motor response is not present, the stimulator is turned off, and injectate deposited. If a motor response is elicited, the current is turned down to approximately 0.5 mA. If a response is still present at 0.5 mA, the needle position on the screen is verified and/or withdrawn, and the process repeated. The use of both monitors in this way has been termed 'dual guidance' or 'protective nerve stimulation' [41].

There are few data on outcomes when using dual guidance compared with ultrasound or nerve stimulation alone, which is not surprising given the overall low incidence of block-related neural injury. Even our best data comparing ultrasound alone to nerve stimulation fails to detect a difference [20]. Despite this, over 45% of surveyed Swiss regional anaesthetists and 25% of surveyed French regional anaesthetists report using dual guidance as their preferred approach [42, 43].

There may be specific cases where dual guidance offers advantages. For example, adductor canal block at the mid-thigh level involves placing local anaesthetic around both the saphenous nerve and the nerve to vastus medialis. The nerve to vastus medialis lies lateral to the saphenous nerve, and is separated from the saphenous nerve by the vasto-adductor membrane. This nerve can be challenging to identify on ultrasound, resulting in it going unblocked or injured during needle advancement towards the femoral artery. Dual guidance in this instance has been shown to reliably identify the nerve to vastus medialis, even when not

Figure 1 Typical peripheral nerve stimulation using a fixed current output of 0.50 mA while an adductor canal block is performed in a child.

viewed on ultrasound, resulting in a block that is both effective (local anaesthetic is deliberately administered at this location) and safe (avoidance of needle-nerve contact) [44]. Similarly, there has been concern raised over the potential for accidental injury to the suprascapular nerve during the retroclavicular block, as the acoustic shadow of the clavicle hides that portion of the needle trajectory and the nerve is not visible [45]. A logical solution is to stimulate during needle advancement to warn of potential needle-nerve contact by watching for a supraspinatus or infraspinatus motor response [46].

The role of nerve stimulation in education

Another complimentary role of nerve stimulation in the era of ultrasound guidance is the ability to provide learners with a 'functional confirmation of the anatomical image'. While skill in learning ultrasound guided procedures can be acquired steadily and quickly with experience, the concomitant use of nerve stimulation may shorten time to proficiency for some block procedures. Axillary brachial plexus blockade provides a good example, as the anatomical arrangement of the four branches of the plexus is notoriously variable [47], and the post-cystic enhancement artefact deep to the axillary artery is commonly mistaken for the radial nerve (Fig. 2). Teaching trainees to seek out each individual nerve during this block and correlate images with each evoked motor response of the upper extremity helps to improve their understanding of these anatomical arrangements. In addition, observing the sudden appearance of a motor response as a needle 'pops' through a fascial plane provides valuable information about needle/fascial interplay and strengthens understanding of relationships between nerve, fascia and muscle. Since the most common novice error is advancing the needle without viewing it [48], nerve stimulation may provide a 'safety net' for the teacher. An unexpected motor response, especially when the current intensity is set to a high level, can warn of impending needle-nerve proximity and encourage re-evaluation of perceived needle tip position.

There are few studies addressing how swiftly block procedures can be learned with ultrasound vs. nerve stimulation. Luyet et al. compared learning curves of trainees performing axillary brachial plexus block before the introduction of ultrasound (i.e. with a four-nerve multi-stimulation technique alone) to those trainee curves after ultrasound had been established in their centre [49]. The ultrasound group also used nerve stimulation with a fixed output as protective stimulation but did not require a motor response. The ultrasound group achieved a 90% success

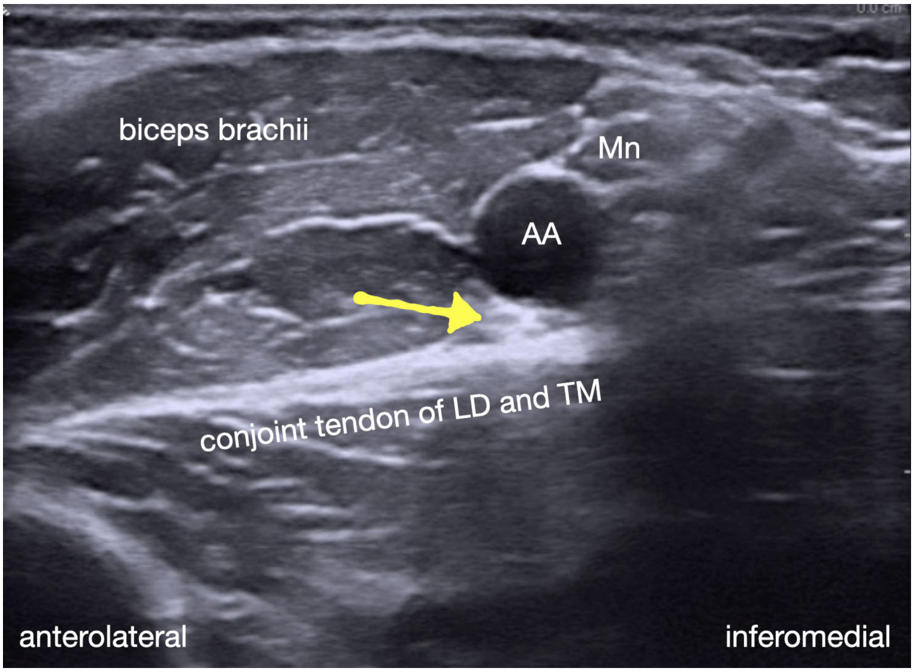

Figure 2 Ultrasound image of axillary brachial plexus anatomy, showing questionable sonographic landmarks for several of the target structures. The ulnar and musculocutaneous nerves (unlabelled) are not apparent. The radial nerve is not well-demarcated, and could easily be confused with post-cystic enhancement (arrow) present deep to the axillary artery. AA, axillary artery; LD, latissimus dorsi; Mn, median nerve; TM teres major.

Table 1 Advantages and disadvantages of nerve stimulation for localising nerves in the setting of ultrasound guided regional anaesthesia.

Advantage	Disadvantage
May be helpful in the setting of deep and/or difficult blocks where ultrasound view is challenging (e.g. parasacral, subgluteal sciatic or obturator nerve)	May be false negative motor responses due to channelling of current away from target nerve
Can differentiate hyperechoic artefact from nerve tissue (e.g. post-cystic enhancement deep to axillary artery versus radial nerve)	May be false positive motor responses due to electrical stimulation of nerves through fascial barriers that subsequently prevent effective spread of local anaesthetic
May enhance understanding of peripheral nerve anatomy by providing a functional confirmation of the anatomical image (e.g. obtaining an evoked motor response of each of the nerves in the axilla to demonstrate anatomical arrangement)	Once a conductive solution is injected (e.g. saline or local anaesthetic), electrical current is channelled along the path of least resistance away from nerve, increasing the current threshold for obtaining an evoked response
	May prolong block performance time, especially if an evoked response is sought for every nerve

Table 2 Advantages and disadvantages of nerve stimulation with respect to block safety in the setting of ultrasound guided regional anaesthesia.

Advantage	Disadvantage
High specificity for intra-neural needle tip placement if evoked motor response < 0.2 mA	False negatives may still occur (needle can be contacting nerve and fail to evoke a motor response)
May serve as 'safety net' for novices and trainees when needle view is not ideal by warning of imminent needle-nerve contact	
May help identify and avoid nerves in the needle path that cannot be viewed due to acoustic shadows (e.g. suprascapular nerve during the retroclavicular block)	
Inexpensive and little training required	

rate within 15 block attempts, while the nerve stimulation group took approximately 30 attempts to achieve 80% success, where it levelled off. These results are not surprising, given the complexity of the multi-stimulation technique.

Disadvantages of nerve stimulation as an adjunct

Given that electrical nerve stimulation can clarify difficult ultrasound interpretation and possibly aid in the prevention of needle-nerve contact, while its use is not universal, we must consider if there is a downside (Tables 1 and 2). Several studies have demonstrated prolonged block procedure times when ultrasound was combined with nerve stimulation compared with ultrasound alone [25, 26, 50]. It is possible this is more clinically relevant when each nerve is being sought and stimulated purposefully, rather than the stimulation being used at a fixed current output to prevent nerve contact. One retrospective analysis of over 26,000 nerve blocks from a German database revealed that the combined technique was associated with increased odds of multiple skin punctures compared with ultrasound alone, whereas ultrasound alone was associated with an increased risk of paraesthesia [51]. In general, there appears to be no substantial or serious disadvantage to employing nerve stimulation as an adjunct to ultrasound guidance during nerve blockade.

Future research directions

Many modern nerve stimulators can measure bioimpedance, the resistance of tissues to electrical current flow. There is some evidence that an intraneural needle tip position is associated with an increase in impedance, compared with an extra-neural needle tip position [52, 53]. This relationship may aid in increasing the sensitivity of nerve stimulation in detecting dangerous needle-nerve contact, but requires further validation in the clinical setting, as well as research into improving the way such information is presented to the clinician so that any such change is easily detected and actionable.

Fascial plane blocks have traditionally been performed without nerve stimulation guidance, as the nerves that lie in intermuscular fascial planes are frequently small and difficult to view on ultrasound. In addition, it is likely that any evoked motor or sensory response would be subtle and challenging to interpret, especially in an anaesthetised patient. Nevertheless, dual guidance (i.e. ultrasound and nerve stimulation) has been used to refine stimulating catheter position in cervical erector spinae plane blocks [54], as well as to reduce local anaesthetic volume during pectoral nerve type-1 (PECS 1) block, [55] although the overall value in these instances remains unclear. Further research into the additive role of nerve stimulation in fascial plane blocks seems warranted, especially for those that are associated with more challenging sonography (e.g. transmuscular quadratus lumborum).

Conclusion

For a few brief years after ultrasound guidance became widespread, there existed two camps: the early ultrasound adopters vs. the traditionalist stimulators, both fiercely defending their chosen method of localising nerves in editorials, anaesthetic departments and at conference pro-con sessions. The implied message was that one of these technologies would emerge victorious after it was proven superior by data. This, of course, was a false premise, because many of us were (and perhaps still are) looking through the wrong lens. Ultrasound was always here to stay the minute it showed the first nerve on the screen. The ability to watch needle and target and bring them together in real time is invaluable. Nerve stimulation is not perfect at finding nerves, but it does add value as a safety monitor and a means to hedge your bets when the image is less than ideal. In the context of safety, asking whether we should use ultrasound or nerve stimulation is akin to asking whether you would prefer seatbelts or airbags in your car. Why would we not choose both, given the additional data they provide and the lack of risk? Nerve stimulation is a technology that, like the best technologies, has pivoted to meet the changing needs of the times. Once a means to find nerves, now it has an adjunctive role in staying away from nerves, along with finding the inconspicuous nerves. There also appears to be a role, although less clear, in helping novices understand the relationship between the ultrasound screen and functional anatomy at the needle tip. As is evident from some recent survey studies, nerve stimulation is still used routinely by many as a component of 'dual guidance'. These data come from one part of Western Europe, and it would be useful to conduct more survey studies of contemporary nerve block practice around the globe.

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