The Requisites of Needle-to-Nerve Proximity for Ultrasound-Guided Regional Anesthesia

A Scoping Review of the Evidence

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Abstract: This scoping review examines the literature to determine whether the position of the needle tip relative to the target nerve is accurately and reliably detected during ultrasound (US)–guided regional anesthesia. The requisites for successful and safe needle tip positioning relative to the target nerve include accurate and reliable needle presentation by the machine, needle interpretation by the operator, nerve presentation by the machine, and nerve interpretation by the operator. Failure to visualize the needle tip is a common occurrence, frequently prompting operators to use needle and probe maneuvers, which are not necessarily based on evidence. Needle tip interpretation often relies on surrogate indicators that have not been validated. The acoustic resolution of modern portable US machines limits the extent to which nerve microanatomy can be reliably presented. Finally, our interpretation of the sonographic end points for local anesthetic injection that best balance success and safety for US-guided regional anesthesia continues to evolve.

What's New: In order to determine whether or not the position of the needle tip relative to the target nerve is accurately and reliably detected during US-guided regional anesthesia, the available literature is reviewed and interpreted to address the following 4 questions:

1. Is the presentation of needle tip by the ultrasound machine accurate and reliable?
2. Is the interpretation of the needle tip image by the operator accurate and reliable?
3. Is the presentation of the nerve by the ultrasound machine accurate and reliable?
4. Is the interpretation of the nerve image by the operator accurate and reliable?

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The introduction of real-time ultrasound (US) guidance is the most important advance in regional anesthesia practice of the new millennium. Compared with traditional nerve localization techniques, US increases overall block success, hastens block onset, and allows a lower volume of local anesthetic to be used.[1–4] Importantly, US also reduces serious complications such as vascular puncture and local anaesthetic toxicity.[1,5] These procedure-related advantages of US are believed to stem from reliable, real-time visualization of needle tip positioning relative to the target nerve and surrounding tissues. Indeed, when compared with US, traditional nerve localization techniques such as mechanical elicitation of paresthesias and peripheral nerve stimulation are limited by their low sensitivity in discriminating the position of the needle tip relative to the target nerve.[6] Accordingly, another purported advantage of real-time US guidance is the potential to avoid hazardous mechanical trauma to the nerve by the needle. While sound in theory, the concept of improved safety with respect to nerve injury has not translated into practice.[7–9] There are now numerous reports of inadvertent intraneural injection despite the use of real-time US guidance,[10–13] with subsequent nerve injury in some cases, presumably due to unrecognized placement of the needle tip inside the target nerve. Indeed, unlike many radiographic still imaging techniques, the quality of real-time sonographic imaging reflects both the intrinsic capacity of the machine's technology as well as the skills of the operator. Therefore, the objective of this literature review was to determine whether the position of the needle tip relative to the target nerve is accurately and reliably detected during US-guided regional anesthesia.

METHODS

Literature Search

Two of the authors (F.W.A. and R.B.) independently searched the US National Library of Medicine database, MEDLINE; the Excerpta Medica database, EMBASE; Cochrane Database of Systematic Reviews; CINAHL; and Cochrane Central Register of Controlled Trials databases. The medical subject headings "ultrasound" and "nerve block" alone and coupled with the results of the search for the keywords "nerve" OR "needle" combined by the Boolean operator AND with the keywords "localization" OR "visualization" OR "detection" OR "identification" OR "recognition" OR "presentation" OR "interpretation" were queried. Gray literature and the bibliographies of included articles were also searched for additional reports that met the inclusion criteria.

Eligibility Criteria

Reports of qualitative and quantitative studies involving both humans and animals were considered, and the search was limited to reports published between January 1960 and March 2014. Only reports published in the English language were included. We sought and retrieved full reports that examined the effects of various interventions, techniques, maneuvers, or technologies on the presentation and interpretation of both needle and targeted nerve during US-guided regional anesthesia. Reports describing research related to any intervention that may facilitate the recognition of needle-to-nerve proximity and/or the impact of this intervention on the success and/or efficacy and/or safety of the US-guided intervention were selected. The review was not limited to randomized controlled trials, and all levels of evidence[14] were considered. Studies examining US-guided procedures for chronic pain management were excluded as these were recently addressed elsewhere.[15]

Two of the authors (F.W.A. and R.B.) reviewed the retrieved reports; the decision to include qualifying reports was based on relevance rather than level of evidence and was reached by consensus.

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Disagreements were resolved by a voting process that involved all 3 authors.

Data Analysis

A standardized data extraction form was used to review and evaluate the results of included reports. Two of the authors (F.W. A. and R.B.) independently charted the included reports; assessed their design, interventions, and outcomes; and assigned a level of evidence using the US Department of Health and Human Services Agency for Health Care Policy and Research Levels of Evidence.[14]

Study Design

The literature examining the reliability and accuracy of needle tip positioning relative to the nerve during US-guided regional anesthesia is emerging or evolving and comprises a diverse array of research methodologies. To address our objective for the present study, we therefore decided a priori that a scoping design would be more appropriate than a traditional systematic review, which has a very limited focus and is directed by a finite study question.[16] The aim of a scoping review is 2-fold: (i) to comprehensively explore the nature, relevance, and size of existing evidence and (ii) to specify the research question(s) that will further develop the knowledge base and guide future focused research.[17–19] To that end, the guidelines for conducting a scoping review described by Arksey and O'Malley[20] were followed in the preparation of this manuscript. Accordingly, we identified any recurring themes related to the requisites of needle-to-nerve proximity addressed in these reports. The final levels of evidence as well as the themes addressed were designated by consensus, and the included reports were classified according to these recurring themes.

In keeping with guidelines for conducting a scoping review,[20] the authors also consulted with Prof. Vincent W. Chan, a leading authority on US-based regional anesthesia, for his opinion regarding the identification of recurring themes, the classification of retrieved reports according to these themes, and the validity of the conclusions derived by the authors.

RESULTS

Our search yielded 14,847 citations; 13,279 abstracts were identified after duplicate citation removal. From these, 12,991 did not meet the inclusion criteria and were excluded. We reviewed a total of 288 full-text articles and included 106 of these articles in this review (Fig. 1).

The review identified 4 recurring themes representing elements that must be in synchrony for accurate and reliable positioning of the needle tip relative to the target nerve during US-guided regional anesthesia, namely, (i) the machine's sonographic presentation of the needle tip, (ii) the operator's interpretation of the needle tip image, (iii) the machine's sonographic presentation of the nerve, and (iv) the operator's interpretation of the nerve image. Based on these themes, herein we interpret the available literature in an attempt to address the following 4 questions:

(1) Is the presentation of needle tip by the US machine accurate and reliable?
(2) Is the interpretation of the needle tip image by the operator accurate and reliable?
(3) Is the presentation of the nerve by the US machine accurate and reliable?
(4) Is the interpretation of the nerve image by the operator accurate and reliable?

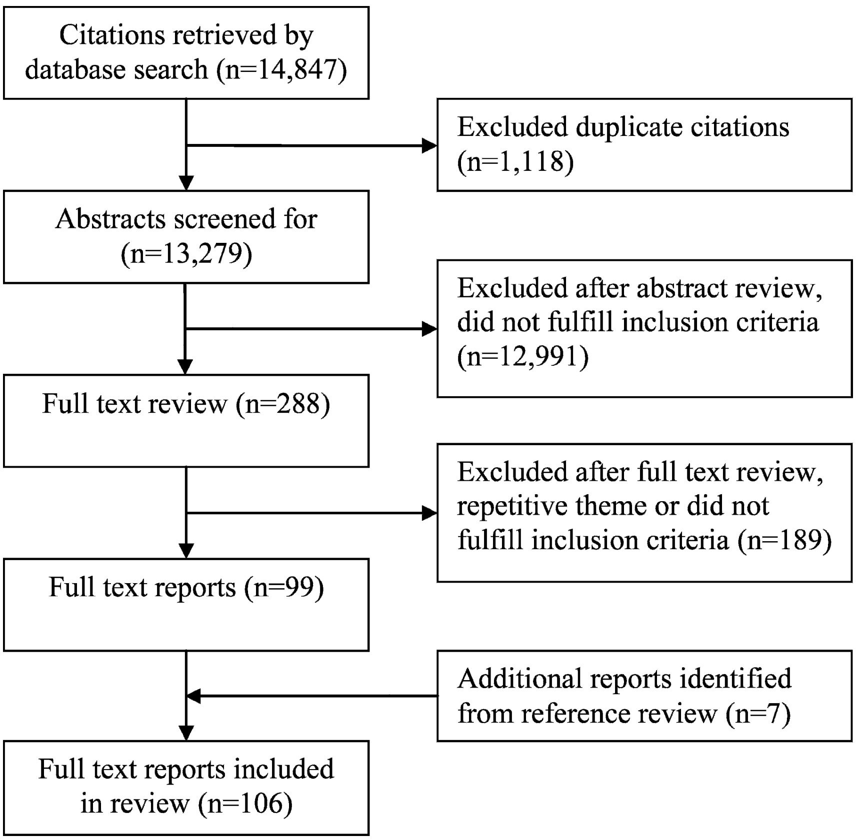

FIGURE 1. Selection process. Flowchart summarizing the study selection process and depicting retrieved, included, and excluded studies.

Table 1 categorizes the various maneuvers, techniques, and technologies identified through the literature search that may facilitate recognition of needle-to-nerve proximity according to the themes identified and summarizes the corresponding level of evidence.

Needle Tip Presentation

Visualizing the needle tip during US-guided regional anesthesia, and indeed other US-guided procedures, can be challenging.[21]

TABLE 1. Evidence-Based Recommendations to Enhance Detection of Needle-to-Nerve Proximity, Assessed Using the US Department of Health and Human Services Agency for Health Care Policy and Research Levels of Evidence[14]

Needle tip presentation

- Needle-probe alignment and needle tip identification improve with operator competency (level IIa)
- Educational tools such as phantoms and simulation facilitate skill acquisition, needle-probe alignment, and needle tip detection (level IIa)
- Transducer manipulation improves needle tip visualization (level IIb)
- Needle manipulation to alter the angle of insonation can improve needle tip visibility (level III)
- Needle manipulation to alter bevel orientation improves needle tip visibility (level IIb)
- Larger needle gauge increases US beam reflectiveness and may facilitate needle tip detection (level III)
- Echogenic needles improve needle tip visibility (level IIa)
- Needle priming and pumping assist in needle and needle tip detection (level IIb)
- Needle guides assist in needle tip visualization (level IIb)
- Beam steering enhances needle tip visibility (level IIb)
- Image compounding technology enhances the sonographic presentation of block needles (level IIa)
- Needle recognition software facilitates identification of needle tip position (level IIb)
- Vibrating devices and Doppler effect permit estimation of needle tip position (level III)
- Coupling US with magnetic resonance imaging improves the accuracy of needle tip detection (level IIb)
- Needle-integrated optical fiber hydrophone can facilitate needle tip identification (level III)
- Photoacoustic tracking may facilitate needle and catheter detection (level III)
- Three-dimensional US imaging facilitates needle tip visualization (level IIb)
- Four-dimensional US imaging can facilitate needle tip tracking (level III)
- High-definition US imaging improves needle tip visibility (level IIb)
- Robotic-assisted guidance can improve needle tip recognition (level III)

Needle tip interpretation

- Operator competency enhances needle tip recognition (level IIa)
- Tissue movement is a surrogate measure of needle tip position (level III)
- Hydrolocation is useful to estimate needle tip position (level IIb)
- Bubble injection can facilitate needle tip recognition (level III)
- Needle tracking assists in interpreting needle trajectory and needle tip recognition (level III)

Nerve presentation

- Tissue harmonic imaging can enhance nerve visualization (level III)
- Spatial compound imaging can improve nerve presentation (level III)

Nerve interpretation

- Nerve swelling is indicative of intraneural injection (level IIb)
- Development of concentric hypoechoic halo in the targeted nerve is indicative of intraneural injection (level IIb)

Poor needle tip visibility is responsible for failure rates as high as 3.7% for thyroid,[22] 4.5% for liver,[23] and 7.5% for breast US-guided needle biopsies.[24] Similarly, the failure of first cannulation attempt during US-guided central venous access procedures is reported to be 9.8%,[25] whereas failure of the first amniocentesis attempt during the third trimester is reported to be 9%.[26] In the context of regional anesthesia, the importance of accurate needle tip presentation cannot be overstated as evidenced by several reports of serious complications following inadvertent injection of local anesthetic inside blood vessels and nerves despite the use of US-guidance in the hands of skilled operators.[8,27–29]

Regardless of whether the needle approach is in-plane or out-of-plane with respect to the US beam, the quality and accuracy of the needle tip presentation depend on proper alignment of the 1-mm-thick US beam with the needle tip, which is considerably less than 1 mm in diameter for most regional anesthesia needles. While some nonclinical studies suggest that visualization of a needle tip is easier using the in-plane approach,[30] contemporary recommendations do not advocate 1 needle approach—in-plane versus out-of-plane—over the other as both have advantages and limitations.[31] Indeed, the risk of misinterpreting the needle shaft for the needle tip persists irrespective of the needle approach. Operator training increases the likelihood of needle tip visualization. Although no evidence-based guidelines exist indicating the number of procedures required to master needle tip visualization during peripheral nerve blockade,[31,32] data from Sites and colleagues[33] suggest that at least 80 US-guided blocks may be required before novices can consistently visualize the needle tip during needle advancement. The use of educational tools such as phantoms and practical simulation has been demonstrated to improve needle probe alignment and needle tip presentation.[34–39]

Both transducer and needle manipulation by the operator are commonly used to optimize needle tip presentation. Transducer rotating, tilting, and sliding[40] as well as the "walk down,"[41] a maneuver whereby the needle is inserted at a distance from the target to permit easier needle tip identification with shallow angles of insonation before progressively moving to steeper angles, are popular maneuvers used to improve needle tip presentation for the in-plane and out-of-plane techniques, respectively, although evidence supporting enhanced needle tip visibility with these maneuvers is lacking. Modifying the angle of insertion to vary the needle-US beam angle of insonation[42,43] and altering the bevel orientation[43,44] have been described to enhance needle tip visibility, albeit the extent of improvement has not been systematically quantified. Although these techniques may improve the presentation of the needle shaft, they are not necessarily effective in visualizing the needle tip.[45]

Technical nonoperator factors also influence the sonographic presentation of the needle tip. Large-gauge needles possess a greater reflective surface that can enhance visualization[43] but are not routinely used in regional anesthetic practice. The use of echogenic needles is gaining popularity.[46] By reflecting a larger proportion of the incident US beam,[47,48] echogenic needles have been shown to improve needle visibility in phantoms[49] and cadavers,[50] particularly in deeper blocks requiring steeper needle trajectories, although evidence of a clinical benefit is scant at present.[48] Priming the needle,[43] pumping the stylet by performing a repetitive in-and-out movement inside the needle[51,52] while using a motion detection algorithm,[53] and using larger gauge needles[43,54] and some devices such as mechanical[55,56] and optical needle guides[57] have been suggested to improve needle visibility, but again, their clinical utility has not been definitively demonstrated. Ultrasound machine features, such as beam steering technology,[58] image compounding,[59] and needle recognition software (SonoSite, Bothell, Washington; GE Healthcare, Waukesha, Wisconsin), are thought to improve needle tip and shaft presentation. Color Doppler coupled with needle vibrating devices,[60–64] magnetic resonance imaging coupled with US imaging,[65] needle-integrated optical fiber hydrophones,[66] photoacoustic tracking,[67] and 3-dimensional,[68] 4-dimensional,[69] and high-definition[70] US imaging are further promising technologies whose utility in needle tip presentation during nerve blocks has yet to be demonstrated. Most recently, the use of robotic assistance for US-guided nerve blocks has been reported in order to ensure consistent alignment between the US beam and needle tip and, as such, reliable needle tip presentation.[71,72]

Needle Tip Interpretation

Accurate and reliable presentation of the needle tip by the US machine is only useful if the needle tip can be interpreted as such by the provider. Evidence suggests that operator competency, achieved through education, training, and practice, facilitates acquisition of the necessary needle tip identification and interpretation skills and improves overall block success rates.[34–39]

Using B-mode US, the needle tip is most often presented as a hyperechoic dot on an image composed of millions of other white dots. Ultrasound beam attenuation and a decline in resolution with an increasing depth of targeted nerves further complicate needle tip interpretation. Whether an in-plane or an out-of-plane approach is used, the diversity of surrogate indicators used to facilitate needle tip interpretation and their routine use in daily practice underscores the challenges of needle interpretation. Tissue movement when the needle is advanced or jiggled[73] may help the provider estimate the position of an otherwise obscure needle tip. Similarly, hydrolocation by injection of small volumes (0.5–1 mL) of fluid may serve the same purpose by creating a dark anechoic pocket and accentuating the needle tip.[74] Injection of microbubbles, a variant of hydrolocation, can facilitate recognition of the needle tip but may also result in deterioration of the image quality.[75,76] Importantly, however, none of these surrogate indicators of needle tip position have been validated radiographically in live subjects or by anatomical dissection in cadaver studies. More recently, novel electromagnetic needle tracking systems such as the SonixGPS (Ultrasonix, Richmond, British Columbia, Canada)[77] and the eTRAX Needle Guidance System (CIVCO, Kalona, Iowa)[78] have been introduced. Much like global positioning system devices commonly used in motor vehicles, these electromagnetic needle tracking systems detect the actual needle tip position and display the projected needle trajectory on the US screen. Such applications may prove especially useful to indicate the needle tip position when performing deep peripheral nerve blocks or neuraxial procedures, but the current supporting evidence is limited to case series.[79,80]

Nerve Presentation

The sonographic presentation of the target nerve varies depending on its size, internal architecture (ie, echotexture),[81] and the echogenicity of the surrounding tissues.[76,82–84] The connective tissue inside nerves appears hyperechoic, whereas the neural components (fascicles) appear hypoechoic, and this connective tissue intertwined with neural components contributes to the distinctive honeycomb appearance of most peripheral nerves.[85]

In order to reliably interpret what is presented on the US screen during nerve imaging, the operator must first understand what cannot be presented by US. Most modern clinical-grade US machines operate in the 2.5- to 20-MHz frequency range, which generally permits presentation of structures greater or equal to 1000 μm.[86–93] In order for a tissue structure to be presented as a discrete and distinct image on the US screen, the machine's intrinsic acoustic resolution must be greater than the actual size of target structure. As such, US is seldom sufficient to accurately and reliably present the small terminal nerve branches that innervate the tissue of interest. Indeed, it is these small terminal nerve branches that are often the indirect yet ultimate target for sensory blockade, prompting some operators to use US to guide local anesthetic infiltration of large volumes of local anesthetic solution adjacent to readily visible bony tissue or in between anatomical fascial planes rather than target the larger, visible, and possibly mixed motor/sensory nerves upstream.

Similarly, US cannot accurately and reliably present the fine connective tissue layers and neural components inside a peripheral nerve. Most nerve fascicles[81,94] (size = 100–1000 μm)[95] and the perineurium (size = 5–25 μm),[96] the epineurium[97] (size = 200–3000 μm),[83,98,99] and the recently described paraneural sheath[82,84] of peripheral nerves are smaller than the machine's capacity for lateral resolution. Indeed, this limitation of US resolution has been illustrated in a cadaveric study by Orebaugh and colleagues,[100] wherein conventional US resolution failed to identify the epineurium of the brachial plexus at the interscalene level. In addition, Silvestri and colleagues[101] noted that only a third of the total number of fascicles in a peripheral nerve may be presented using US and attributed this to both the limited lateral resolution of US as well as the inability of US to present fascicles unless their trajectory is perpendicular to the incident beam. Finally, changes in nerve trajectory or angulation, malpositioning of the neural structure on the US screen,[33] the absence of identifiable sonographic landmarks that can aid in target identification,[102] the presence of fat whose echogenic properties matches that of nerves around the targeted nerve,[81] and the lack of acoustic mismatch between the nerve and its surrounding tissue in general[103–105] are all factors that can hinder nerve presentation irrespective of its size. Tissue harmonic imaging,[106] spatial compound imaging,[107] and adaptive processing are technologies available on many modern portable US machines and may be combined to improve picture clarity by reducing artifacts and speckle; however, no definitive evidence exists to support their efficacy in visualizing nerve tissue in particular.

Nerve Interpretation

The sonographic characteristics of the target nerve and resultant local anesthetic distribution that reliably predicts a successful block following injection have not been defined. While circumferential injection may be required for some nerves, such as the sciatic nerve[108,109] and median nerve,[110,111] it has not been shown to be a requirement for other nerves. Similarly, as with our understanding of sonographic nerve structure[112] and its associated connective tissue layers,[113] the sonographic characteristics of a safe versus dangerous injection are not known.[114] While experts agree that intraneural injection should be avoided,[115,116] it has been suggested that a 9%[117] or even 15%[118] increase in the cross-sectional area of a nerve may be required before an operator is even able to accurately interpret an intraneural needle tip position. Bigeleisen performed deliberate intraneural injection at the axillary[114] and supraclavicular[119] levels of the brachial plexus without any electrophysiological or clinical sequelae and designated the development of a "hypoechoic halo" and nerve swelling as end points indicative of intraneural injection. Sala-Blanch et al[13] performed sciatic nerve blocks at the level of the popliteal fossa and designated local anesthetic injection that produces a "hypoechoic halo around the nerve" or "concentric hypoechoic area around the nerve 2 to 3 cm proximal to the injection site"[118] as subepineural and did not detect any evidence of nerve injury. While nerve swelling is reliably indicative of intraneural injection[120–122] and may potentially be associated with nerve injury, the exact needle tip position that produces the "halo" and the "concentric hypoechoic" signs is controversial. More recently, Andersen and colleagues[84] described the paraneural sheath enveloping the sciatic nerve and proposed that the aforementioned pattern of spread, which had previously been interpreted as subepineural,[13,118,123] was in fact subparaneural[124] and not intraneural. Nevertheless, an alarming rate of paresthesias,[84,125] nerve swelling,[70,84] and even long-term neurological sequelae[84] has still been reported with deliberate subparaneural injection. Such controversies underscore the nascent stage of our collective understanding of sonographic neurological microanatomy in the context of regional anesthesia practice.[13,118]

DISCUSSION

Based on our scoping review of the literature, we found that very few of the strategies and tools commonly used to position the needle tip in close proximity to the target nerve during routine US-guided regional anesthesia practice are soundly based in evidence. Techniques such as hydrolocation and the elicitation of tissue movement that are used regularly to infer the position of the needle tip have not been validated. Fundamental practical considerations such as the quality of needle tip presentation and interpretation for in-plane compared with out-of-plane needle approaches and the operator learning curves that support an accurate and reliable needle-nerve relationship during in-plane compared with out-of-plane approaches remain undefined. Moreover, the numerous technologies and devices recently developed to assist with needle and nerve presentation and interpretation suggest that these requisites can be challenging to achieve, are largely undiscovered, or may even be misunderstood. Indeed, Dr Alon Winnie's[126] timeless dictum, "When there are problems with any regional technique, look for the cause first on the proximal end of the needle," resonates still in the modern era of US-guided nerve blocks. There is sound evidence that operator training improves the reliability and accuracy of both the presentation and interpretation of the needle tip and its position. Finally, the optimal sonographic relationship between the needle tip position and the target nerve is unknown. One distinct advantage that US may offer over other nerve localization techniques is the ability to estimate how far the needle tip is from the targeted nerve, rather than how close it is. Indeed, more conservative US-guided "stay-away" nerve block techniques are beginning to populate the literature,[127,128] including injection into muscles, along fascial planes, or perivascularly instead of perineurally.[129] As our understanding and appreciation of the possibilities and limitations of US guidance for regional anesthesia continue to evolve, our present goal must be to determine the location where the needle tip can be accurately and reliably positioned relative to the target nerve in order to achieve successful and safe peripheral nerve blockade within a reasonable time.

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