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Features of Ultrasound Techniques in Performing Peripheral Regional Blocks

Dobrenko Olga
Resident doctor in anesthesiology and intensive care medicine, Siegen Medical Center Germany, Siegen

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Abstract

The article reviews the development and modern features of ultrasound techniques in the performance of peripheral regional blocks. As requirements steadily mount for effectiveness and safety in perioperative analgesia, this study finds relevance in efforts directed toward optimizing views of both neural structures and the needle, with lowered risks for complications to occur. The purpose is to enumerate the main physico-technical characteristics of ultrasound systems, together with improved transducer manipulation techniques, that play a role in increasing the level of accuracy and informativeness regarding peripheral blocks. The novelty of the research lies in the comprehensive comparison of linear and convex probes according to penetration depth and resolution criteria, the systematic analysis of basic transducer movements (slide, tilt, rotate, fan) and the optimal sequence of settings (depth, overall gain, TGC, dynamic range), as well as in the discussion of modern needle-visibility enhancement technologies—from echogenic needles and beam-steering to passive magnetic tracking and deep-learning algorithms. Additionally, the integration of triple monitoring—ultrasound, nerve stimulator, and manometric pressure control—is proposed as a rational safety standard. The main conclusions demonstrate that selecting a probe based on nerve depth, sequentially optimizing image parameters, and employing additional technological solutions significantly enhance the nerve/fascial-plane contrast, improve needle-tip tracking, and reduce the incidence of intraneural and vascular injections. A multilevel control system ensures the timely detection of hazardous situations without prolonging procedure time, and the implementation of computer technologies opens prospects for further

improvement of precision and operator training. This article will be useful to regional anesthesiologists, educators, and researchers engaged in the development and implementation of ultrasound methods in peripheral regional anesthesia.

Keywords: ultrasound navigation, peripheral regional blocks, transducer, safety, echogenic needle, triple monitoring

Introduction

Since the first experiments by P. La Grange in 1978, when a Doppler transducer was used solely to locate the subclavian artery during a supraclavicular block, ultrasound has gradually evolved from an auxiliary landmark into a fully fledged method for direct visualization of the needle and nerve (Grange et al., 1978). The real breakthrough occurred in the mid-1990s: Kapral's group in Vienna was the first to perform a block under continuous B-mode guidance, and a few years later, Canadian researchers provided a detailed description of the sonoanatomy of the brachial plexus, which accelerated the adoption of the technique into training programs and clinical protocols (Orebaugh, 2018). Over the subsequent two decades, the miniaturization of scanners, improvements in resolution, and the advent of echogenic needles have rendered the methodology truly bedside: today, portable devices are available in most operating rooms and emergency departments.

Meta-analyses have consistently confirmed the clinical benefits of ultrasound guidance. A Cochrane review of 32 randomized trials (2,844 patients) demonstrated that the likelihood of achieving a block adequate for surgery is nearly three times higher with ultrasound guidance (OR 2.94; 95% CI 2.14–4.04), while the need for supplemental anesthesia is reduced by more than 70% (OR 0.28; 95% CI 0.20–0.39) (Lewis et al., 2015). Safety is also enhanced: according to another meta-analysis, the risk of inadvertent vascular puncture decreases when guidance is provided by nerve stimulation alone (Abrahams et al., 2009). These figures illustrate the sustained interest in the technique, which increases first-attempt success rates, accelerates block onset, allows for reduced volumes of local anesthetic, and concurrently lowers the incidence of bleeding, LAST, and conversion to general anesthesia. Together, these factors make ultrasound-guided peripheral regional blocks an indispensable tool in modern perioperative analgesia, positioning their further development as a key growth area in regional anesthesiology.

Materials and Methodology

The materials and methodology of the present study are based on an extensive analysis of 19 key publications, including phantom experiments, clinical randomized trials, meta-analyses, and technical guidelines. The theoretical framework comprised classic studies that traced the evolution from Doppler-based devices (Grange et al., 1978) to modern, high-resolution, portable ultrasound scanners (Orebaugh, 2018). Meta-analyses have broadly validated the clinical benefits of ultrasound guidance in peripheral blocks, providing a detailed description of how effective and safe the technique is. Technical parameters identified as critical and affecting image quality have been discussed by Lewis et al. (2015) and Abrahams et al. (2009).

Several approaches were incorporated in this study. A comparison analysis of ultrasound probes, linear (10–15 MHz) and convex (2–5 MHz), was adopted from the works of Delvi (2011) and NYSORA (2022) regarding nerve depth and resolution requirements. A systematic review of manipulation techniques for the transducer was also conducted, based on data from Mao et al. (2021), who demonstrated that tilt and rotation angles significantly affect needle visibility. Image-adjustment settings, including depth, overall gain, TGC, and dynamic range, were content analyzed through recommendations by Pescatore (2024) and NYSORA (2022) to sequence controls optimally for clear visualization of fascial planes. Fourth, an evaluation of needle-visibility enhancement technologies was undertaken, including reviews by Chin et al. (2008), Ruíz et al. (2014), and Hebard & Hocking (2011), as well as phantom experiments by Johnson et al. (2017), which demonstrated the advantages of magnetic tracking.

Results and Discussion

Against the backdrop of proven clinical efficacy of ultrasound navigation, it is precisely the physico-technical parameters of the device that determine whether the operator will visualize the nerve and needle as clearly as expected. For most superficial blocks, when the target structure lies no deeper than 3 cm, a 10–15 MHz linear transducer is preferred: at the upper limit of this range, the lateral resolution reliably distinguishes the epineurium and small-caliber vessels (Delvi, 2011). For deeper nerves (> 4–5 cm), a 2–5 MHz convex probe is more logical. However, the lower frequency reduces detail; it is compensated for by increased penetration depth and a larger field of view (NYSORA, 2022). Regardless of the transducer type, the focal zone should be set 1–2 cm deeper than the target. In this way, the main beam narrowing coincides with the target zone, thereby increasing nerve/fascial-plane contrast.

After probe selection, transducer manipulation techniques play a pivotal role. The four basic movements—slide, tilt, rotate, and fan—constitute a three-dimensional scanning of tissues without changing the skin contact point. Sliding along the presumed nerve path helps locate the primary anatomical landmark; a slight tilt aligns the acoustic beam axis perpendicular to the structure, increasing returned echoes; rotation switches the image between transverse and longitudinal projections; and fan-shaped oscillation, while maintaining the same contact point, allows illumination of the nerve at different depths. Experimental data indicate that excessive tilt (> 45°) impairs alignment of the needle with the ultrasound beam and reduces the success of in-plane punctures. In contrast, moderate rotation enhances nerve-contour visibility, as schematically illustrated in Figure 1 (Mao et al., 2021).

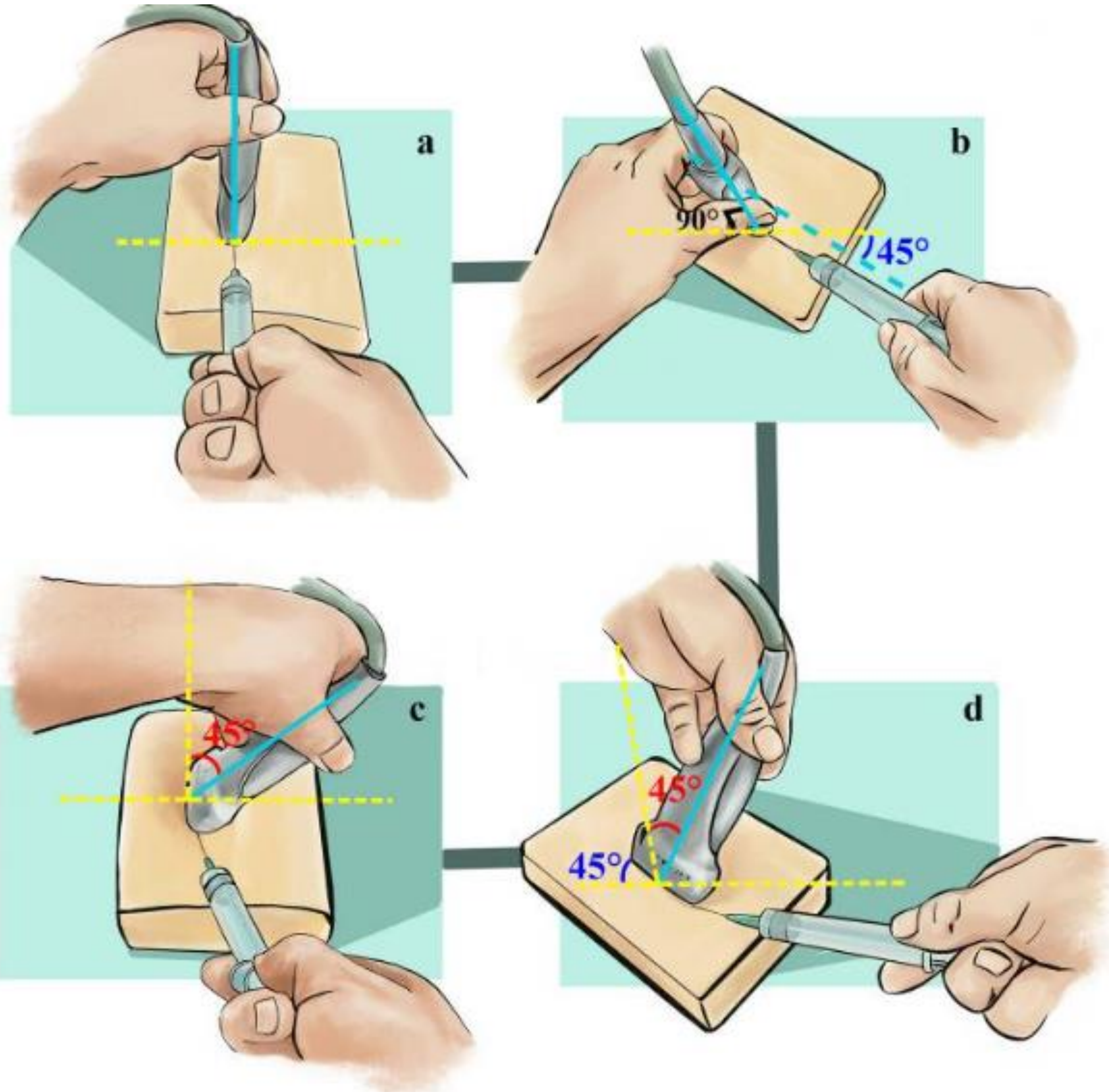

Fig. 1. A schematic drawing of the four insertion views in the phantom study (Mao et al., 2021)

(a) Neutral view, the long axis of ultrasound probe was along the operator's visual axis and ultrasonic beam was vertical to the surface of gel phantom; (b) 45°-rotation view, there is a 45° angle between the long axis of probe and the operator's visual axis (or sagittal plane); (c) 45°-tilt view, there is a 45° angle between the ultrasonic beam and the vertical line (or the surface of gel phantom); (d) 45°-rotation plus 45°-tilt view, there is 45° angle between the long axis of probe and the operator's visual axis (or sagittal plane), while there is another 45° angle between the ultrasonic beam and the vertical line. Yellow dashed line: Vertical/horizontal reference line; Blue solid line: direction of ultrasonic beam; Green angle: rotation angle; Red angle: tilt angle.

Even the optimal transducer position will not yield an informative image without proper signal-processing settings. The imaging depth should be set so that the nerve lies in the middle or lower third of the screen; in this configuration, most scanners will automatically optimize gain and frame rate. The overall gain is adjusted until the vessels appear hypoechoic, and the nerve exhibits a uniform gray-white honeycomb texture. Excessive gain generates noise and blurs the fascial boundaries. A dynamic range of 60–80 dB provides a sufficiently gradated gray scale to distinguish the epineurium, whereas over-compression of the range produces a high-contrast but less informative image (NYSORA, 2022). Console TGC sliders enable the selective brightening or darkening of deeper layers, thereby equalizing brightness across the entire tissue column. This sequential optimization—depth → overall gain → TGC → dynamic range—takes mere seconds yet renders critical details conspicuous (Pescatore, 2024).

Once depth, gain, and dynamic range are optimized, the primary challenge becomes the simultaneous visualization of the needle and the spread of local anesthetic. The needle acts as a metallic specular reflector, so its contrast depends on the angle between its axis and the ultrasound beam; even slight deviation induces anisotropy, causing the needle to disappear. In practice, this necessitates continuous adjustment of the needle trajectory or transducer tilt to maintain perpendicular insonation of the shaft, preserving continuous depiction of the tip and minimizing blind segments of the needle path, as detailed in needle-visibility reviews for ultrasound guidance (Chin et al., 2008).

The choice of the puncture plane determines control over this geometry. With an in-plane approach, the entire needle shaft is imaged, facilitating tip tracking and reducing the likelihood of paraneural contact. A randomized trial of femoral nerve blocks demonstrated intraneural contact in only 9% of in-plane procedures versus 64% of out-of-plane procedures (Ruíz et al., 2014). At the same time, analgesic efficacy and catheter dwell time did not differ, underscoring that safety is governed by tip visibility rather than by plane selection alone.

Hardware innovations can further improve needle visibility. In a randomized controlled trial, the use of the Sonoplex echogenic needle increased the median proportion of needle-tip visibility from 40–60% to 80–100% of the total needle path, despite a steeper insertion angle (Hebard & Hocking, 2011). Additional techniques described in the NYSORA technical guide include beam-steering (virtual electronic beam tilting) and speckle-reduction filtering, which all enhance the signal-to-noise ratio and needle-tissue contrast (NYSORA, 2022).

Computer-assisted technologies extend these capabilities. In a phantom study, passive magnetic tracking of the needle reduced the mean positioning error from 3.5 mm to 1.5 mm (–57%). It increased the first-pass success rate from 76% to 89%, with the optimal insertion angles illustrated in Figure 2 (Johnson et al., 2017).

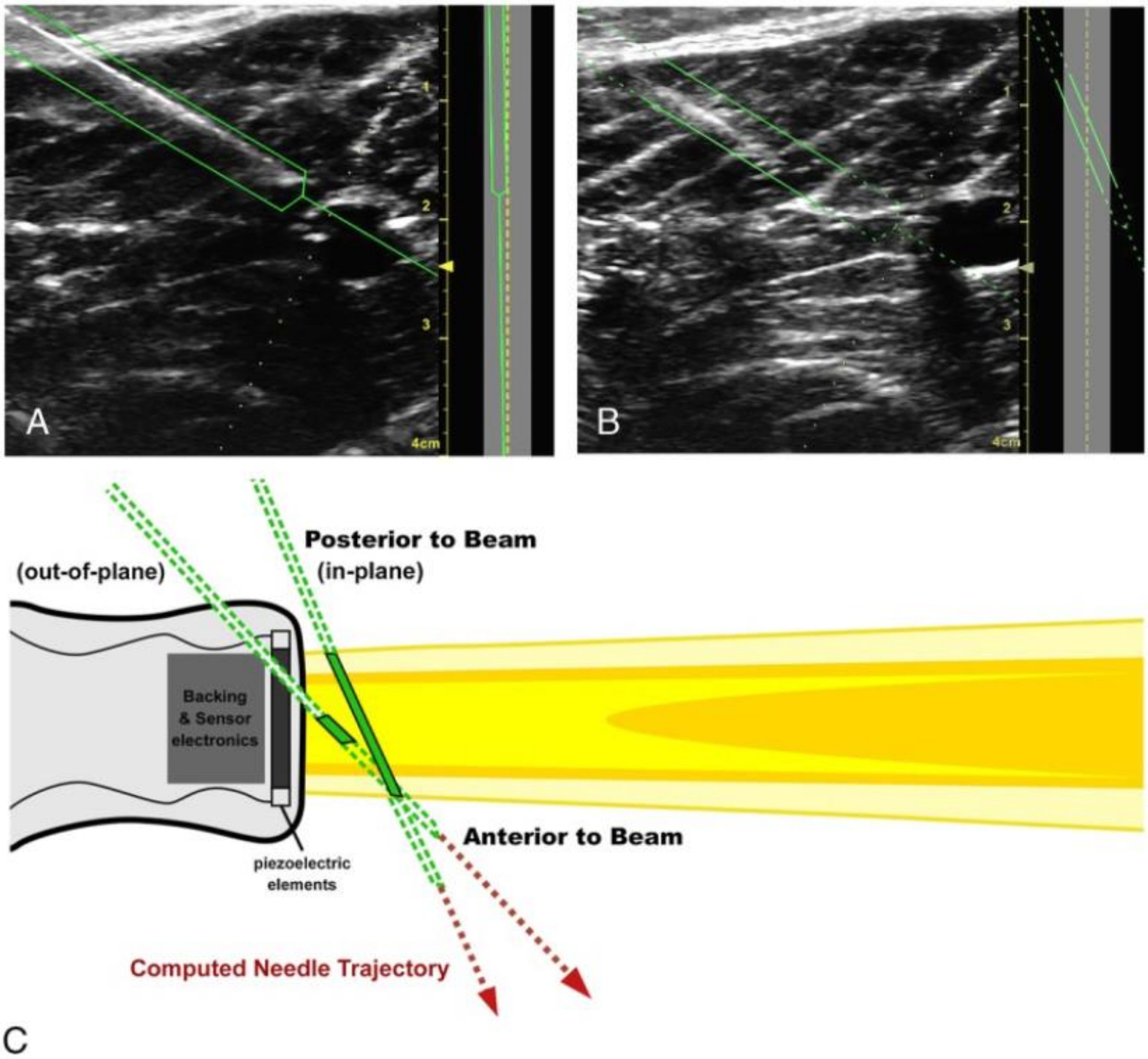

Fig. 2. Photographs of the NGT interface showing the correct needle angle relative to the beam for the IP approach (Johnson et al., 2017)

(A) and correction based on the NGT solid-to-dotted green lines, indicating that the operator should alter the needle position relative to the beam. Needle guidance technology can help anesthesiologists recognize common technique issues that occur when the angle is inadvertently altered by ergonomic issues, operator fatigue, or inadvertent movement of the transducer (B). A solid green line represents the needle segment in the beam, and calculated positions of anterior and posterior segments are represented by dotted green lines. The NGT interface facilitates visualizing the needle position relative to the beam cross-section (A, B: left). The corresponding appearance of the needle IP and OOP relative to the linear array probe is demonstrated in the diagram (C).

Deep-learning algorithms, according to a scoping review, can identify anatomical landmarks and needle contours in real-time, facilitating operator training and potentially reducing complication rates (Viderman et al., 2022).

Finally, block success is confirmed by monitoring the spread of the injectate. Hydrodissection creates a fluid cushion that visibly expands the fascial plane before anesthetic administration. A circumferential spread around the nerve—the donut sign—correlates with faster onset and longer block duration (Huang et al., 2018). Continuous ultrasound monitoring of these patterns enables the timely adjustment of needle position or injection volume, transforming the procedure from semi-intuitive to fully controlled.

Even with accurate ultrasound visualization, block safety depends on prompt recognition of nerve contact, excessive injection pressure, and proximity to vessels; accordingly, triple monitoring—combining ultrasound, nerve stimulation, and pressure sensing—is increasingly utilized. A prospective study demonstrated that this combination identified 33 potentially hazardous situations that would have otherwise gone unnoticed with ultrasound alone, and no postoperative neurological complications occurred in any patient (Pascarella et al., 2021).

Use of the peripheral nerve stimulator remains the simplest adjunctive test of needle position. In vivo and phantom experiments have confirmed that a motor response at ≤ 0.2 mA almost invariably indicates intraneural tip placement, whereas the absence of response at ≥ 1 mA reliably excludes intraneural positioning but does not guarantee optimal perineural proximity (Bigeleisen et al., 2009). Thus, a low stimulation threshold has high specificity but low sensitivity; a negative stimulation test should not replace visual control, while a positive response warrants adjustment of the trajectory.

The second component—manometric monitoring—has likewise been validated. Animal and clinical studies demonstrate that injection pressure above 15–20 psi correlates reliably with needle placement inside a nerve trunk or root (Rambhia & Gadsden, 2019). In human observations, when the needle tip was more than 1 mm from a brachial plexus root, initial pressures remained below 15 psi, whereas intentional subepineurial positioning consistently raised pressures to 30 psi or more (Smith et al., 2021). Simple disposable pressure-indicator manometers, connected between the syringe and extension tubing as shown in Figure 3, do not encumber the operator's hand and provide an immediate visual alert when thresholds are exceeded, which is especially valuable during training.

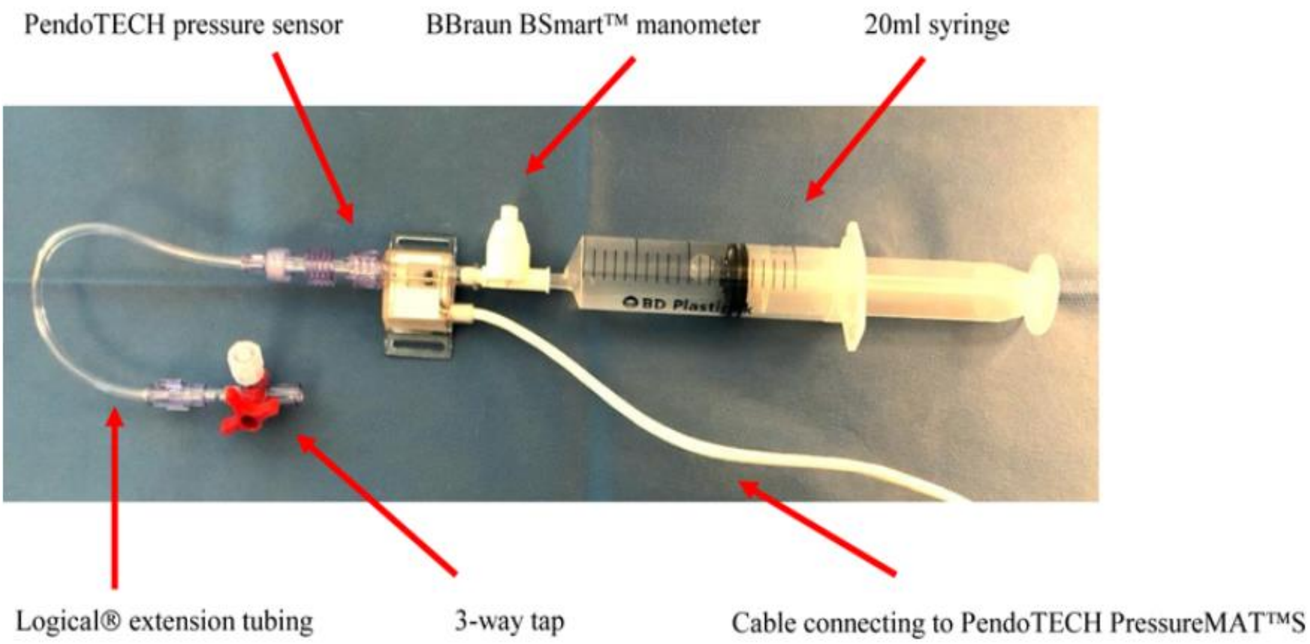

Fig. 3. Assembly of equipment (Smith et al., 2021)

Third line of defense — Doppler modes. Color or power Doppler is engaged before puncture to distinguish small vessels, which often course through neurofascial bundles. In healthy volunteers, their presence in the brachial plexus region reaches 86–90% (Hahn & Nagdev, 2014). A meta-analysis of 13 randomized studies demonstrated that adding ultrasound guidance, which included routine Doppler screening, reduces the risk of vascular puncture nearly sixfold (RR 0.16; 95% CI 0.05–0.47) compared with nerve stimulation alone (Abrahams et al., 2009). Continuous monitoring of the color map during anesthetic injection helps to promptly detect turbulent flickering of the jet in the event of inadvertent intravascular needle placement and to cease the injection before the development of LAST.

Collectively, these three complementary signals — the visual image, the electrical response, and pressure dynamics — form a multilevel error-warning system. It adds virtually no time to the procedure but significantly reduces the likelihood of intraneural injection, hematoma, and systemic local anesthetic toxicity, making it a rational safety standard for most peripheral blocks.

When applying the principles of triple monitoring to specific clinical situations, the operator must remember that each block has its own sonoanatomy and imaging characteristics. It is precisely the combination of proper transducer selection, probe-manipulation techniques, and accurate interpretation of the spread pattern of the solution that determines whether the on-screen image will translate into a reliable analgesic effect.

In the supraclavicular block of the brachial plexus, a high-frequency linear transducer is used, positioned parallel to the clavicle to simultaneously visualize the subclavian artery, the contour of the first rib, and the cluster of nerve trunks. After a small hydrodissection, the needle is advanced into the lateral pocket adjacent to the artery; uniform encirclement of the bundle by the solution indicates correct positioning and minimizes the risk of pneumothorax.

For the transverse abdominis plane block, the probe is placed along the mid-axillary line, sequentially revealing the external and internal oblique muscles, behind which the thin fascial layer of the transversus abdominis is identified. Injection into this layer produces a linear echo signal between the fasciae, extending cranially and caudally over a significant distance, providing reliable analgesia after abdominal interventions.

The erector spinae plane block in the region of the spinal extensors is performed with a low-frequency convex probe, guided by the transverse-process shadow and the bright fascial plane superficial to the muscles. After tissue separation with solution, it distributes longitudinally in both directions, ensuring multisegmental analgesia during thoracic and abdominal surgeries.

For the sciatic block via the infrapiriformis approach, the probe is positioned between the sciatic notch and the greater trochanter, requiring deep visualization and continuous monitoring of the gluteal vessels. The popliteal variant, by contrast, is performed with a high-frequency linear transducer. At the level of the nerve bifurcation, the needle is advanced in the longitudinal plane, and a ring-like spread of the solution around both branches is confirmed. This approach increases the likelihood of a complete sensorimotor block and significantly reduces the risk of vascular puncture.

Although the general principles of imaging and pressure monitoring are universal, nuances — from the choice of imaging plane to the volume of injectate and the desired echo pattern — vary among different blocks. The ability to recognize these subtle differences transforms the ultrasound image from a static picture into a predictable clinical outcome.

Thus, the successful performance of peripheral regional blocks largely depends on the harmonious combination of three key components: correct selection and adjustment of the ultrasound transducer, refined probe-manipulation technique, and use of adjunct monitoring tools (nerve stimulator and manometry). Minimization of anisotropy during needle visualization, along with optimization of depth, gain, and dynamic range, ensures a clear depiction of the nerve and fascial planes. Additionally, triple monitoring reliably detects potentially dangerous situations. The interplay of modern technologies — from echogenic needles and beam steering to machine-learning algorithms and magnetic tracking — allows the procedure to be transformed from semi-intuitive to strictly controlled, increasing the efficacy and safety of blocks. Below, we discuss practical recommendations and algorithms for selecting the optimal technique in specific clinical scenarios.

Conclusion

This review highlights the key role of the physico-technical parameters of ultrasound systems and the mastered probe manipulation techniques in achieving optimal visualization of peripheral nerves and the needle. Adjusting the frequency and geometry of the transducer according to the depth of the nerve trunk ensures a balance between resolution and penetration. Precise tuning of depth, overall gain, TGC, and dynamic range allows for clear delineation of delicate anatomical structures and fascial boundaries. At the same time, a streamlined sequence of image optimization occupies minimal time and significantly enhances the informativeness of the scan.

Mastery of basic movements — sliding, tilting, rotation, and fan-like rocking — creates a volumetric three-dimensional representation of the anatomy without the need to change the contact point. The correct selection of the puncture plane (in-plane vs. out-of-plane) and the use of echogenic needles further augment the operator’s capabilities, minimizing blind spots and improving needle-tip tracking. The incorporation of beam steering and other software filters additionally enhances needle–tissue contrast and reduces the impact of anisotropy.

Particular attention is given to the multilevel safety system — triple monitoring, which integrates ultrasound imaging, nerve stimulation, and manometric pressure control. This combination enables the timely detection of dangerous situations related to paraneural or intravascular needle placement, significantly reducing the risk of complications (intraneural injections, hematomas, LAST) without prolonging procedure time.

Finally, the integration of computer technologies — from passive magnetic tracking to deep-learning algorithms — opens prospects for further improving accuracy and operator training. These developments are capable of automating the recognition of anatomical landmarks and needle trajectory, which in the future will render the procedure even more controllable and safe.

In summary, the successful execution of peripheral regional blocks today is determined by the harmonious integration of ultrasound equipment selection and settings, refined scanning techniques, and modern monitoring tools. Further development and implementation of innovative technologies promise even greater improvements in the efficacy and safety of the method, reinforcing its status as an indispensable tool of modern regional anesthesia.

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