

**ULTRASOUND-GUIDED REGIONAL ANESTHESIA: ADVANCES, CURRENT EVIDENCE, CLINICAL APPLICATIONS, AND FUTURE PERSPECTIVES — A SCOPING REVIEW**

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ABSTRACT Ultrasound-guided regional anesthesia (UGRA) has fundamentally reshaped perioperative pain management by enabling real-time visualization of neural, vascular, and fascial structures during peripheral nerve and plane blocks. Over the past two decades, refinements in transducer technology, image processing, needle-tracking software, and, more recently, artificial-intelligence (AI)-assisted anatomical recognition have progressively lowered the technical barriers historically associated with landmark- and nerve-stimulator-guided approaches. This scoping review synthesizes literature on the technological evolution of UGRA, summarizes comparative evidence on its efficacy and safety relative to conventional localization methods, maps its expanding clinical applications across surgical, obstetric, pediatric, geriatric, trauma, and chronic-pain settings, and outlines emerging directions including AI-guided needle navigation, robotic assistance, tele-mentoring, and simulation-based training. The available evidence indicates that ultrasound guidance shortens block performance and onset time, reduces local anesthetic dose requirements, and carries a favourable safety profile, although its incremental benefit for overall block success and neurological complication rates compared with nerve stimulation remains only modestly established for some block types. Persisting challenges include an operator-dependent learning curve, cost of equipment, and heterogeneous training standards. Continued integration of AI, augmented reality, and structured competency-based curricula is likely to further standardize practice and broaden access to UGRA, including in resource-limited settings.

KEYWORDS : Ultrasound-Guided Regional Anesthesia; Peripheral Nerve Block; Artificial Intelligence; Perioperative Analgesia; Scoping Review

1. INTRODUCTION

Regional anesthesia has evolved considerably since its origins in surface-landmark-based and paresthesia-elicitation techniques. The introduction of peripheral nerve stimulation in the latter half of the twentieth century improved localization by eliciting motor responses to confirm proximity to a target nerve, but it remained an indirect, non-visual technique dependent on anatomical assumptions and patient factors such as body habitus and anatomical variation. The adoption of portable, high-resolution ultrasound into anesthetic practice from the early 2000s onward introduced, for the first time, the ability to directly visualize target nerves, surrounding vasculature, needle trajectory, and the spread of local anesthetic in real time.

This shift has been described as one of the most significant practice-changing developments in modern anaesthesiology. Ultrasound guidance is now embedded in enhanced recovery after surgery (ERAS) protocols, opioid-sparing multimodal analgesia strategies, and ambulatory surgical pathways, reflecting its role not merely as a procedural aid but as a facilitator of broader perioperative care goals. At the same time, the field continues to evolve rapidly, with artificial intelligence, fusion imaging, and robotic-assistance technologies now entering clinical and investigational use.

Given the breadth and pace of this literature, a scoping review approach is well suited to map the range of technological advances, evaluate the current state of comparative evidence, chart clinical applications across patient populations and care settings, and identify emerging directions and evidence gaps. This review addresses four guiding questions: (i) What technological advances have shaped the evolution of UGRA? (ii) What does current comparative evidence show regarding efficacy and safety relative to non-ultrasound techniques? (iii) Across which clinical domains has UGRA been applied? and (iv) What future developments are anticipated to influence practice?

2. METHODOLOGY

This review follows the scoping review framework originally described by Arksey and O'Malley and subsequently refined by Levac and colleagues, reported in accordance with the Preferred Reporting

Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR). A structured search was conducted across PubMed/MEDLINE, Embase, the Cochrane Library, and Google Scholar for English-language literature published between 2005 and 2026, using combinations of the terms “ultrasound-guided regional anesthesia,” “peripheral nerve block,” “artificial intelligence,” “nerve stimulation,” and “regional anesthesia” combined with “clinical application,” “outcomes,” or “review.”

Eligible sources included peer-reviewed systematic reviews, meta-analyses, randomized controlled trials, and narrative reviews addressing technological development, comparative efficacy or safety, clinical application, or future directions of UGRA. Case reports, animal studies, non-English publications, and conference abstracts without full-text availability were excluded. Extracted data were charted descriptively under four domains corresponding to the review questions above. As a scoping review, formal methodological quality appraisal and pooled quantitative synthesis were not undertaken; findings are presented narratively, which should be considered when interpreting the strength of conclusions drawn.

3. Technological Advances in Ultrasound-Guided Regional Anesthesia

3.1 Transducer and Image-Processing Advances

High-frequency linear transducers (typically 10–18 MHz) now provide the spatial resolution required to identify superficial peripheral nerves, fascial planes, and small-calibre vessels. Compound and harmonic imaging, needle-enhancement algorithms, and beam-steering software have improved needle-tip conspicuity, a historically difficult aspect of in-plane and out-of-plane approaches. The proliferation of compact, portable, and wireless handheld ultrasound devices has also extended point-of-care access to regional anesthesia beyond the operating theatre, into emergency departments, intensive care units, and resource-limited settings.

3.2 Three-Dimensional and Doppler Imaging

Three- and four-dimensional ultrasound, together with colour and power Doppler, allow clearer delineation of vascular structures adjacent to target nerves, reducing the risk of inadvertent intravascular

injection or vessel puncture, particularly in vascular-rich regions such as the supraclavicular fossa and inguinal crease.

3.3 Artificial Intelligence-Assisted Anatomical Recognition

The most notable recent advance has been the emergence of AI-based image-enhancement platforms that overlay real-time, colour-coded annotations of nerves, vessels, muscle, and fascia onto conventional B-mode images. Deep-learning-based systems such as the ScanNav Anatomy Peripheral Nerve Block platform have been evaluated for their ability to assist anatomical identification; accuracy evaluations comparing AI-highlighted images against expert consensus have reported high concordance rates, and prospective accuracy studies have similarly demonstrated close agreement between AI-identified and expert-identified anatomical structures in peripheral nerve and plane blocks [10, 11]. These tools are positioned primarily as assistive rather than autonomous technologies, intended to support anatomical recognition and reduce inter-operator variability, particularly for trainees and occasional users of UGRA.

3.4 Fusion Imaging, Robotics, and Simulation

Fusion of ultrasound with pre-procedural cross-sectional imaging (CT or MRI) has been explored for anatomically complex or deep blocks, such as paravertebral or lumbar plexus blocks, where surface ultrasound visualization alone may be limited. Early-stage robotic and semi-autonomous needle-guidance platforms are under investigation to standardize needle trajectory and depth control, though these remain largely at the research and prototype stage. In parallel, AI-enhanced simulation platforms are being developed to translate theoretical anatomical knowledge into procedural competency, aiming to shorten learning curves and reduce complications such as inadvertent vascular puncture during early training.

4. Current Evidence

Comparative evidence on UGRA has accumulated steadily since the mid-2000s. Early systematic reviews and meta-analyses comparing ultrasound guidance with peripheral nerve stimulation reported consistent reductions in block performance time and onset time, along with reduced local anesthetic volume requirements and lower rates of vascular puncture [2, 4]. A widely cited meta-analysis of randomized controlled trials found a modest but statistically significant increase in block success rate with ultrasound guidance compared with both all non-ultrasound techniques and nerve stimulation alone [4]. However, a Cochrane systematic review examining the same comparison found the evidence for improved overall success less consistent across block types and settings, noting methodological heterogeneity across the available trials [3].

With respect to safety, no included studies in early qualitative reviews reported serious complications attributable specifically to ultrasound guidance, and subsequent work examining neurological complications after regional anesthesia has found the overall incidence to be low regardless of localization technique, with no clear demonstration that ultrasound guidance eliminates the risk of nerve injury [6, 7]. For continuous peripheral nerve catheters, comparative evidence suggests only modest differences in catheter placement success between ultrasound and nerve-stimulator guidance, though ultrasound reduces placement time [8].

More recent evidence has focused on AI-assisted UGRA. Prospective accuracy studies and multicentre evaluations of AI image-enhancement platforms have reported high concordance between AI- and expert-identified anatomical structures, and narrative reviews published through 2025–2026 describe consistent improvements in anatomical recognition accuracy and operator confidence, particularly among trainees [10, 11, 13]. However, robust randomized evidence directly linking AI assistance to improved patient-centred outcomes — such as block success, complication rates, or patient satisfaction — remains limited, and most available studies to date have focused on process measures such as identification accuracy and time-to-recognition rather than clinical endpoints.

Table 1: Summary of Representative Comparative Evidence on Ultrasound-guided Regional Anesthesia and AI-assisted Ultrasound Guidance.

Study / Source	Comparison	Design	Key Finding
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Abrahams et al., 2009 [2]	US vs. nerve stimulation	Systematic review & meta-analysis of RCTs	US associated with improved block quality, reduced performance time and vascular puncture
Walker et al., 2009 (Cochrane) [3]	US vs. alternative localization techniques	Cochrane systematic review	Limited high-quality RCT evidence; benefit on overall block success inconsistent across block types
Gelfand et al., 2011 [4]	US vs. all non-US techniques	Meta-analysis of 16 RCTs	Higher success rate with US (RR ≈ 1.11) vs. non-US and vs. nerve-stimulator alone
Ilfeld, 2017 [8]	US vs. nerve stimulation for perineural catheters	Narrative synthesis of RCTs/meta-analyses	Modest differences in catheter success; US reduces placement time
Gungor et al., 2021 [10]	AI-assisted vs. conventional image interpretation	Prospective accuracy study	High concordance between AI-identified and expert-identified anatomical structures
Bowness et al., 2023 [11]	AI-highlighted vs. conventional B-mode ultrasound	Multicentre evaluation	AI overlay improved anatomical structure identification accuracy (up to ~99.7% in scoring)

5. Clinical Applications

5.1 Perioperative Surgical Anesthesia

UGRA is now standard practice for upper-limb procedures via interscalene, supraclavicular, infraclavicular, and axillary brachial plexus approaches, and for lower-limb surgery via femoral, adductor canal, sciatic, and popliteal blocks. Direct nerve visualization allows tailored local anesthetic deposition and dose reduction while facilitating single-injection and continuous catheter techniques for extended postoperative analgesia.

5.2 Truncal and Fascial Plane Blocks

The description of ultrasound-guided fascial plane blocks — including the transversus abdominis plane (TAP), rectus sheath, pectoral nerve (PECS I/II), serratus anterior plane, erector spinae plane, and quadratus lumborum blocks — has substantially expanded the scope of truncal analgesia. These techniques are now integral components of opioid-sparing multimodal analgesia within ERAS pathways for abdominal, thoracic, and breast surgery.

5.3 Obstetric, Pediatric, and Geriatric Anesthesia

In obstetric practice, ultrasound assistance improves neuraxial access in parturients with challenging spinal anatomy, while ultrasound-guided TAP blocks provide adjunctive analgesia after cesarean delivery. In pediatric anesthesia, the narrower safety margins for local anesthetic dosing and anatomical variability make direct visualization particularly valuable, supporting more precise, lower-volume block placement [9]. In geriatric patients, UGRA is increasingly favoured for hip-fracture and lower-limb surgery via fascia iliaca and pericapsular nerve group (PENG) blocks, given its association with reduced opioid consumption and its proposed role in mitigating postoperative delirium and cognitive dysfunction risk [14].

5.4 Trauma, Emergency Medicine, and Critical Care

Ultrasound-guided nerve and plane blocks have been increasingly

incorporated into emergency department and trauma pathways, including serratus anterior and erector spinae plane blocks for rib fractures and femoral or fascia iliaca blocks for hip fracture. Systematic review evidence in this setting indicates more rapid and sustained pain relief, reduced opioid consumption, and shorter emergency department stay when performed by trained providers, with a low rate of associated complications [18].

5.5 Chronic Pain Management

Beyond the perioperative period, ultrasound guidance is used for diagnostic and therapeutic nerve blocks in chronic pain practice, including occipital, intercostal, and genicular nerve blocks, allowing more accurate needle placement than surface-landmark techniques alone and potentially reducing the number of needle passes required.

6. Challenges and Limitations

- Operator dependency and a demonstrable learning curve for image acquisition, interpretation, and needle-tip tracking.
- Capital cost of high-resolution ultrasound systems and, increasingly, of AI-enhancement software licensing.
- Heterogeneous and inconsistently standardized training and credentialing pathways across institutions and countries.
- Persistent risk of intraneural injection and nerve injury despite direct visualization, as ultrasound resolution cannot reliably distinguish fascicular structure.
- Limited high-quality randomized evidence linking AI-assisted guidance to patient-centred clinical outcomes rather than process measures alone.
- Variable access to advanced ultrasound and AI-enabled equipment in low-resource and rural healthcare settings.
- Absence of harmonized regulatory frameworks for the clinical validation of AI-assistance devices across manufacturers and jurisdictions.

7. Future Perspectives

Several developments are likely to shape the next phase of UGRA practice. Real-time AI-based tracking that simultaneously identifies nerves, adjacent vasculature, and needle-tip position, with predictive trajectory overlays, may further reduce complication risk and support less experienced operators. Semi-autonomous and robotic-assisted needle-insertion platforms remain an active area of investigation, with the aim of improving trajectory consistency and depth control, though clinical translation will require robust safety and outcome data.

Augmented-reality (AR) headset-based guidance, projecting sonographic and anatomical information directly into the operator's field of view, and tele-ultrasound or tele-mentoring platforms that connect experienced regional anesthetists with remote or trainee operators, may extend both the reach and the safety of UGRA in underserved settings. Integration of AI with large clinical datasets may eventually support personalized local anesthetic dosing and block selection based on patient-specific factors. Finally, AI-enhanced simulation and competency-based training curricula are being developed and evaluated — including ongoing prospective trials — with the goal of accelerating skill acquisition and standardizing procedural competency across training programs.

Realizing these advances will require prospective, adequately powered trials focused on patient-centred outcomes, harmonized regulatory pathways for AI-assistance devices, and structured, competency-based training frameworks endorsed by professional societies such as ASRA and ESRA.

8. CONCLUSION

Ultrasound-guided regional anesthesia has evolved from an adjunctive localization aid into a cornerstone of modern perioperative and chronic pain practice, supported by consistent evidence of improved block performance metrics and a favourable safety profile relative to landmark- and nerve-stimulator-based techniques. Its clinical applications now span surgical anesthesia, truncal and fascial plane analgesia, obstetric, pediatric, geriatric, trauma, and chronic pain settings. The emergence of artificial intelligence-assisted image interpretation, fusion imaging, and early robotic and simulation technologies signals a further phase of refinement, but rigorous outcome-focused research, standardized training, and harmonized regulatory validation remain necessary before these innovations can be considered an established standard of care.

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