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The integration of artificial intelligence in regional anesthesia: perspectives, challenges, and opportunities

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Abstract

Artificial intelligence (AI) presents new opportunities in medicine for enhancing clinical outcomes, professional training, and healthcare organizations.

We emphasize the importance of thoroughly understanding new technologies and defining their potential and limitations, promoting the construction of multidisciplinary collaborations to provide modern, comprehensive anesthesiological training.

Introduction

In recent years, technological advancements and the ability to manage and analyze large volumes of data have revolutionized many areas of medicine, including anesthesiology. In particular, regional anesthesia is undergoing an unprecedented transformation due to the integration of artificial intelligence (AI), which offers new opportunities for improving clinical outcomes, professional training, and healthcare delivery.

The systematic collection and analysis of perioperative data, supported by intelligent systems, now provide a novel analytical perspective on previously achieved results. This approach opens the possibility of highlighting the real impact of different anesthesiological strategies, especially for fragile and critically ill patients, going beyond individual experience or anecdotal evidence.

The position expressed in this document emphasizes the importance of thoroughly understanding the rationale behind these new technologies, clearly defining their potential and limitations, and fostering multidisciplinary collaborations. Such efforts are essential to provide modern, comprehensive anesthesia training that aligns with evolving technological standards.

Artificial intelligence in regional anesthesia: the state of the art

Recent literature demonstrates how AI integration into regional anesthesia, particularly in ultrasound-guided regional anesthesia (UGRA), is enhancing both the precision and efficiency of procedures. Görmüş *et al.*[1] highlight how AI optimizes ultrasound imaging, guides target identification, assists with needle manipulation, and aids in administering local anesthetics, proving particularly useful for both beginners and experienced professionals. Similarly, Karmakar *et al.*[2] report that AI systems can provide real-time guidance during needle placement and generate predictive models to improve procedural accuracy and patient outcomes. Balavenkatasubramanian *et al.*[3] further emphasize that the use of ultrasound combined with AI not only increases the success rates of blocks but also reduces the risk of complications. Recent developments have further refined the AI support in regional anesthesia. Some advanced AI models not only enable automatic identification of nerves, blood vessels, and muscles,[4] but also provide real-time color overlays directly on the ultrasound image. This feature improves the interpretation of sonoanatomy, facilitating the localization of anatomical targets and increasing the precision of blocks, especially in complex cases such as obese patients or deep blocks.

Moreover, AI is evolving toward the integration of clinical big data related to patients, procedures, and drugs, aiming to develop personalized strategies to optimize block performance and reduce complications. Specific AI models have already been created for particularly complex regional blocks, such as the interscalene, supraclavicular, infraclavicular, and transversus abdominis plane (TAP) blocks, as well as the femoral nerve block.[5] These applications are not only educational tools but also clinical assistants capable of increasing procedure success rates and reducing variability between experienced and non-experienced operators.

Numerous studies also emphasize how AI improves the training

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experience for resident doctors. Cai *et al.*[6] showed that the adoption of AI-based perceptual learning systems reduces the incidence of paresthesias during procedures, improving procedural safety and accelerating the learning process.

These findings suggest that AI in regional anesthesia is not merely an auxiliary tool but a valid extension of the anesthesiologist's clinical capabilities.

Machine learning and deep learning: the foundations of artificial intelligence in anesthesiology

The application of AI in medicine is based on a series of computational techniques, with machine learning and deep learning being the most relevant for clinical analysis and image processing.[7-9] These technologies offer new possibilities in anesthesia and perioperative medicine, allowing for the interpretation of large amounts of data, identifying complex clinical patterns, and supporting decision-making.

Machine learning is a subset of AI that enables computers to learn from structured datasets without being explicitly programmed. The algorithm is "trained" on a set of historical data (*e.g.*, medical records or physiological parameters) to recognize associations between variables and predict future events, such as the risk of complications or responses to specific drugs. This approach can be supervised (with labels provided by experts), unsupervised (to discover hidden patterns), or reinforcement-based (to improve subsequent decisions based on feedback).

Deep learning, an advanced form of machine learning, utilizes artificial neural networks with multiple layers, making it particularly effective in analyzing complex signals, such as ultrasound images, intraoperative videos, or physiological signals. In anesthesiology, deep learning has shown promising results in tasks such as automatic recognition of anatomical structures in ultrasound-guided blocks, predicting hypotension risk during anesthetic induction, or automatically classifying respiratory patterns in mechanically ventilated patients.

Training these models relies on annotated clinical datasets, often consisting of thousands or millions of examples collected in real hospital settings. The process involves:

- Data collection: ultrasound images, vital parameters, and clinical annotations.
- Training phase: the model learns to associate inputs (*e.g.*, images) with outputs (*e.g.*, recognized anatomical structures).
- Validation: testing on previously unseen data to verify generalizability.
- Optimization: iterative improvement of model performance.
- (Optional) Continuous learning, based on new data collected in clinical practice. Clinical datasets used for training typically include diverse imaging sources acquired in different conditions (*e.g.*, various probe positions, patient anatomies, or noise levels) and are carefully annotated by multiple experts to reduce inter-observer variability. For example, in ultrasound imaging for peripheral nerve blocks, datasets may include thousands of images with labeled structures such as brachial plexus, axillary artery, and adjacent muscles. Publicly available datasets are rare, but initiatives like the Open Access Series of Imaging Studies (OASIS) or the POCUS dataset repositories are growing.

The performance of AI models in this context is evaluated using standard metrics, including:

- Accuracy: the overall proportion of correct predictions.
- Sensitivity (Recall): the ability to correctly identify true positives (*e.g.*, correctly identifying a nerve when present).
- Specificity: the ability to correctly identify true negatives.
- Precision (positive predictive value): the proportion of predicted positives that are correct.
- Dice coefficient/Intersection-over-Union (IoU): specific to segmentation tasks (*e.g.*, contouring anatomical structures). From an architectural perspective, some of the most effective models in clinical imaging include:
- U-Net: particularly suited for biomedical image segmentation; it captures both local and contextual features, making it ideal for outlining nerves and vessels in ultrasound.
- ResNet (Residual Network): allows very deep networks to be trained by addressing the vanishing gradient problem, commonly used for classification or feature extraction from medical images.
- DenseNet and EfficientNet: explored for their strong performance in visual tasks with limited computational resources.

One of the most mature areas for deep learning applications is automatic interpretation of ultrasound images, as will be illustrated in the next chapter. The use of convolutional neural networks (CNNs) has revolutionized ultrasound for nerve blocks, making it safer and more accessible even for less experienced operators.

These technologies, if well understood and implemented sensibly, do not replace clinical judgment but enhance it, allowing anesthesiologists to act with greater precision, speed, and awareness. The responsible and informed adoption of such tools represents one of the key steps toward transitioning anesthesia and intensive care to a more data-driven and personalized future.

Practical integration of artificial intelligence in ultrasound devices: how it works

To fully understand the practical value of AI in regional anesthesia, it is essential to clarify concretely where and how its integration takes place within ultrasound systems.

The integration can occur:

- In the native software of the ultrasound machine, some recent models, such as the GE Venue™[10] or the Philips Lumify™ AI Edition, already incorporate AI algorithms directly into the machine's operating system.
- As an additional module or external software. Older devices or portable ultrasound machines can connect to AI solutions *via* i) cloud computing: the ultrasound image is sent to remote servers for analysis; or ii) edge computing: processing occurs directly on the portable device *via* dedicated apps or hardware.

These options allow for broader access to AI technology even in settings where a complete ultrasound machine upgrade may not be immediately possible.

Types of AI software for anesthesiology ultrasound

AI software dedicated to regional anesthesia is primarily developed based on computer vision, a branch of AI that automatically interprets medical images; an example is ScanNav™.[11]

AI models and training

Technically, integrated AI relies on CNNs, particularly suited for analyzing medical images. The model training process involves:

- Data collection: ultrasound images annotated by experts with the contours of nerves, vessels, and muscles.
- Supervised training: the model learns to recognize anatomical structures through labeled examples.
- Validation: testing on new, previously unseen images to verify the system's generalization.
- Continuous optimization: some systems experiment with reinforcement learning strategies, improving based on real-time clinical data collected. In ultrasound-specific applications, U-Net is frequently employed for segmentation tasks, while ResNet-based architectures may support the classification of structures or enhance feature recognition layers of hybrid systems. These architectures are often fine-tuned using transfer learning from large image databases such as ImageNet before being specialized on clinical data.

Practical clinical use

During the performance of a peripheral block:

- The operator turns on the AI-integrated ultrasound machine.
- The system automatically analyzes the ultrasound image in real-time.
- Key structures (nerve, vessel, muscle) are highlighted with specific colors.
- An optimal needle trajectory is suggested.
- The system provides dynamic feedback ("correct approach", "reposition needle", *etc.*), improving patient safety and supporting intraoperative decision-making.

Clinical and training benefits improved procedural accuracy

AI assists the anesthesiologist in locating difficult-to-identify anatomical structures, thereby increasing the likelihood of a successful block on the first attempt and reducing the need for multiple needle insertions.

Patient safety

By reducing technical errors (*e.g.*, accidental intravascular injection) and minimizing complications (paresthesias, nerve damage), the use of AI can significantly improve perioperative outcomes.

Enhancing training

AI serves as an extraordinary educational tool. It provides learners with constant visual guidance, aids in understanding complex ultrasound morphology, and accelerates the attainment of technical competence.

Organizational and systemic implications

The introduction of AI in anesthesiology requires a rethinking of perioperative organizational models.

It is necessary to:

- Redefine training pathways by integrating AI technology education as part of anesthesia training.
- Develop guidelines for the use of AI in the operating room, considering technical, legal, and ethical aspects.
- Invest in appropriate technological infrastructure to ensure AI solutions are accessible, even in resource-limited contexts.

Moreover, the adoption of AI systems requires staff trained not only in anesthesiology techniques but also in managing the technological interface, interpreting data, and responsibly using automated tools.

Limitations of AI

Despite the promising potential, current AI tools have limitations. For example, performance may decline with low-quality ultrasound images or in patients with atypical anatomies.[12] Generalizability remains a challenge, as models trained on specific datasets may not perform equally well across different populations or devices. There are also concerns regarding transparency ("black box" models) and the need for continuous validation and regulatory oversight.

The future integration of AI in anesthesia will likely involve multimodal models that combine clinical data, imaging, and laboratory results to provide comprehensive decision support. The combination of AI with augmented reality may also enhance the precision and ease of regional anesthesia procedures, potentially allowing real-time overlay of anatomical structures on the patient's body during scanning.

Another critical limitation is data bias.[12] Many AI systems are trained on datasets collected from specific populations, institutions, or imaging devices. This can introduce biases that affect performance in underrepresented groups or with different machine settings.

Real-time performance constraints may also arise. For AI to be useful in UGRA, especially during dynamic procedures, it must operate in real time with minimal latency. Ensuring this performance without compromising accuracy is technically challenging and computationally intensive.

Integration with clinical workflows is another unresolved issue. AI tools must be seamlessly embedded into existing systems without increasing the clinician's cognitive or administrative workload. If poorly implemented, AI could become a source of distraction or delay rather than support.

Finally, user trust and adoption remain variable. Some clinicians may be hesitant to rely on AI assistance, especially in high-stakes procedures, due to a lack of understanding or confidence in the underlying algorithms. Education and intuitive user interfaces are essential to foster meaningful human-AI collaboration.

Ethical, legal, and safety issues

Incorporating AI systems into clinical anesthesiology practice introduces new challenges:

- Data privacy: the use of images and clinical data to train models raises issues related to patient privacy protection.
- Clinical responsibility: in case of error, responsibility remains with the operating physician, even if the incorrect suggestion comes from the AI system.
- Algorithmic bias: if training datasets are not representative, AI may express biases that could compromise effectiveness or safety in certain patient groups.
- Decision-making autonomy: AI should be viewed as a support to clinical decision-making and not as a substitute for the anesthesiologist.
- Algorithm transparency and explainability: many AI systems, particularly deep learning models, operate as "black boxes", offering little insight into how specific decisions are made. This

opacity can reduce clinicians' ability to evaluate, trust, or challenge AI outputs, ultimately affecting patient safety.

- Secondary use of clinical data: health data collected for care purposes may be reused for commercial applications or shared with third parties without patient awareness or explicit consent. This raises ethical concerns around data ownership, patient autonomy, and possible misuse.
- Impact on the doctor-patient relationship: the increasing reliance on algorithmic suggestions may risk depersonalizing care, reducing human interaction, and potentially undermining the patient's trust in their physician.
- Impact on interprofessional collaboration: AI tools may disrupt established clinical hierarchies or workflows, creating tensions or misunderstandings between colleagues if the distribution of responsibility and authority is not clearly defined.

Obviously, it is crucial to address these challenges proactively to ensure ethical and safe AI implementation.

Multidisciplinary collaborations: a necessity

To fully leverage the potential of AI in regional anesthesia, it is essential to establish collaborations with experts in various fields: data science, bioengineering, IT, and clinical medicine. These collaborations will guarantee the creation of high-quality, effective, and patient-centered solutions.

Future perspectives

Looking ahead, AI is expected to evolve toward multimodal models that integrate clinical, imaging, and laboratory data for holistic decision-making. The combination of AI with augmented reality (AR) could transform UGRA by enabling real-time overlays of anatomical maps, enhancing both training and procedural accuracy. These innovations may soon become part of routine anesthetic practice, further bridging the gap between technology and human expertise.

In addition, future systems may incorporate real-time feedback loops, allowing AI models to continuously learn and adapt from new data acquired during procedures, thus improving performance and personalization over time. The development of federated learning frameworks, which enable collaborative training across multiple institutions without sharing patient data, could also help address data privacy concerns while increasing the diversity and generalizability of training datasets.

Another promising direction is the integration of natural language processing and voice-command interfaces, which could allow anesthesiologists to interact with AI tools hands-free during sterile procedures. AI may also assist in predictive analytics, identifying patients at a higher risk of complications or block failure, thereby allowing for more proactive planning.

Conclusions

Artificial intelligence is set to play an increasingly crucial role in regional anesthesia by enhancing precision, safety, and clinical training, ultimately benefiting both anesthesiologists and patients. Successful integration will require adequate training, adherence to ethical standards, and multidisciplinary collaboration. As AI continues to evolve, it promises to revolutionize how regional blocks are performed and taught, leading to more robust, personalized, and user-friendly tools. Despite ongoing challenges, continued research and development will support anesthesiologists in delivering high-quality care across diverse clinical environments.

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