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Emerging Techniques and Technological Advancements in Dental Local Anaesthesia and Modern Anaesthetic Delivery Devices used in dentistry

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ABSTRACT:

Dental local anaesthesia has evolved significantly with advances in pharmacology, digital technology, and minimally invasive delivery systems. Dental local anaesthesia is the foundation of pain control in modern dentistry and is essential for restorative, endodontic, periodontal, and oral surgical procedures. Although conventional syringe-based anaesthesia remains effective, injection-related pain, anxiety, delayed onset, and occasional anaesthetic failure continue to present clinical challenges. Recent advances focus on improving patient comfort, enhancing anaesthetic efficacy, reducing tissue trauma, and increasing operator precision. Contemporary techniques aim to improve patient comfort, reduce injection pain, increase anaesthetic success, and enhance procedural efficiency. Contemporary innovations include computer-controlled local anaesthetic delivery (CCLAD) systems, Single Tooth Anaesthesia (STA), vibrotactile devices, intraosseous anaesthesia systems, needle-free jet injectors, buffered local anaesthetic solutions, electronic dental anaesthesia, and digitally guided injection technologies. Evidence suggests that CCLAD devices provide the most consistent reduction in pain during anaesthetic deposition, while intraosseous systems improve success in difficult mandibular cases. Vibrotactile and cryotherapy-assisted methods show promising results for reducing needle insertion discomfort, particularly in pediatric and anxious patients. This review critically summarizes recent developments, compares modern devices with conventional techniques, and discusses future directions including artificial intelligence-assisted injection guidance and personalized anaesthetic protocols..

INTRODUCTION

Pain control is fundamental to modern dentistry. Although conventional local anaesthetic techniques remain effective, failures may occur because of anatomical variation, inflammation, anxiety, and technical factors. Recent innovations focus on improving accuracy, comfort, onset time, and tissue preservation while reducing fear associated with dental injections. Effective pain management is one of the most important determinants of successful dental treatment and patient satisfaction. Local anaesthesia allows clinicians to perform invasive dental procedures with minimal discomfort while maintaining patient consciousness and cooperation.

Controlled, minimally invasive, digitally aided, patient-specific delivery systems have replaced the traditional syringe-and-cartridge method in dentistry local anesthesia. Dental anxiety, treatment acceptability, and patient participation are all affected by the fear of injection, even tho traditional nerve-block and infiltration methods are still cost-efficient and clinically effective. The main technical constraints include difficulties in penetrating tissues, swelling from quick deposition, individual differences in anatomy, insufficient diffusion thru thick cortical bone, decreased anesthetic efficacy due to inflammation, and injection pressure and flow control being dependent on the operator. In the published article, these are highlighted as major contributors to pain and infrequent anesthetic failure.

Despite significant pharmacological advances, dental injections remain one of the greatest sources of anxiety and fear among patients. The traditional aspirating syringe, although reliable, is associated with pain during needle penetration and tissue distension caused by rapid anaesthetic deposition. Recent innovations have therefore focused on improving delivery devices, injection techniques, and anaesthetic formulations to provide a more comfortable and predictable clinical experience. Modern technologies now include computer-controlled delivery systems, vibrotactile devices based on the gate-control theory of pain, intraosseous anaesthesia systems, needle-free jet injectors, buffered local anaesthetic solutions, and digital guidance technologies that improve injection accuracy and patient comfort.

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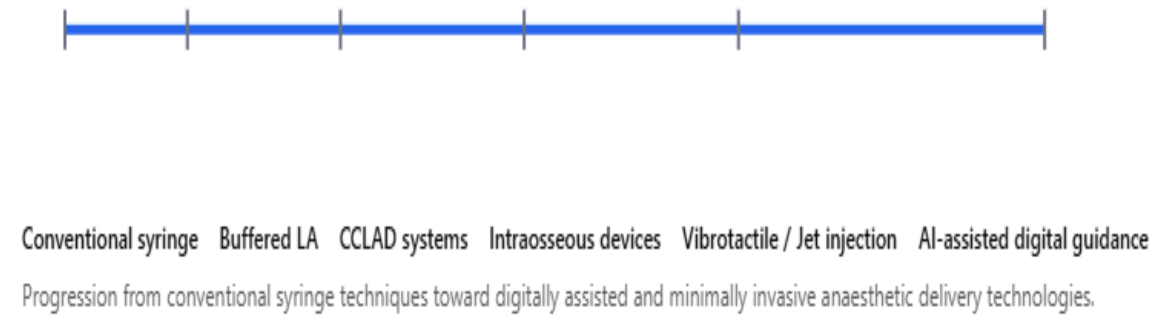


Figure 1. Evolution of dental local anaesthesia

Therefore, the focus of recent studies has shifted to managing the physical parameters of delivery in addition to the pharmacological capabilities of the anesthetic solution. A number of factors can impact the patient's actual experience in the clinic, including the injection pressure, tissue resistance, needle placement, penetration depth, anatomical site, and deposition time. These advancements include computer-controlled local anesthetic delivery, intraosseous injection devices, needle-free injection, buffered solutions, electronic analgesia, digitally guided methods, counter-stimulation based on vibration, and intraosseous injection (ITAS). Computing local anesthetic delivery, intraosseous anesthesia, vibrating stimulation, and electronic dental anesthesia were the four categories into which contemporary devices were placed in a scoping review that was conducted in 2024 and based on 107 pertinent sources.

Conventional Local Anaesthesia

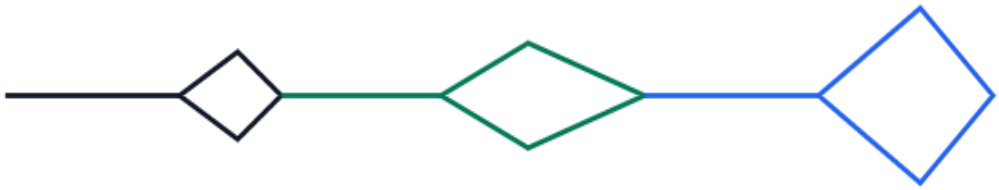
Common techniques include infiltration, inferior alveolar nerve block, mental/incisive block, periodontal ligament injection, and intraosseous injection. Lidocaine remains widely used, while articaine has gained popularity because of its superior diffusion through bone and rapid onset. Conventional dental local anaesthesia is administered using a cartridge syringe, needle, and local anaesthetic solution. Common techniques include infiltration anaesthesia, inferior alveolar nerve block, mental and incisive nerve block, periodontal ligament injection, and intraosseous injection. Lidocaine with epinephrine has historically been the most widely used agent, while articaine has gained popularity because of its superior diffusion through cancellous bone and rapid onset of action. Conventional techniques remain effective for most clinical procedures; however, failure rates are higher in mandibular molars with irreversible pulpitis and in patients with anatomical variations. Pain during injection is primarily related to needle penetration and rapid expansion of tissues during anaesthetic deposition.

Buffered Local Anaesthesia:

Buffering sodium bicarbonate into local anaesthetic cartridges raises pH, decreases the burning sensation during injection, and may shorten onset time. Clinical studies report improved patient comfort and faster pulpal anaesthesia in selected procedures.

Computer-Controlled Local Anaesthetic Delivery (CCLAD)

Devices such as The Wand and Single Tooth Anaesthesia (STA) system regulate flow rate and pressure electronically. Benefits include reduced injection pain, improved precision, controlled deposition, and better patient acceptance, especially in children and anxious adults. Computer-controlled local anaesthetic delivery systems represent one of the most significant technological advances in dental anaesthesia. These devices regulate the flow rate and pressure of anaesthetic deposition electronically, producing a slow and controlled injection that minimizes tissue distension and discomfort. The pen-like handpiece provides improved tactile feedback and ergonomic control compared with a conventional syringe. The Wand/Compu Dent system was the first widely adopted CCLAD device, and later systems included Comfort Control Syringe, Calumet, Sleeper One, Anaject, and other digitally regulated injectors. The 2024 scoping review identified CCLAD devices as the most extensively researched category of modern anaesthetic technology, with The Wand and STA systems accounting for the majority of published studies. Many investigations reported reduced pain during anaesthetic deposition, particularly during palatal injections, although results for pain during needle insertion were more variable.



Conventional syringe CCLAD controller Slow controlled deposition

Computer-controlled delivery systems regulate flow rate and pressure, improving injection precision and reducing discomfort during anaesthetic deposition.

Figure 2. Computer-controlled local anaesthetic delivery (CCLAD)

Fig.3 Intraosseous

Advantages of CCLAD

Reduced injection pain during anaesthetic deposition.

Improved precision and tactile control.

Better patient acceptance, particularly among children and anxious adults.

More consistent flow rate and pressure.

Improved success during palatal and periodontal ligament injections

Single Tooth Anaesthesia (STA) System:

The Single Tooth Anaesthesia (STA) system is an advanced form of CCLAD specifically designed for periodontal ligament injections. The device provides real-time pressure feedback that assists the clinician in locating the optimal periodontal ligament space before anaesthetic deposition. By delivering anaesthetic at an extremely slow rate, STA can selectively anaesthetize individual teeth without producing prolonged numbness of the lips, tongue, or surrounding soft tissues. This feature is particularly useful for bilateral mandibular procedures and endodontic treatment of difficult-to-anesthetize teeth. Clinical studies have shown improved pulpal anaesthesia success in certain cases of irreversible pulpitis and enhanced patient comfort compared with conventional intraligamentary injections.

Intraosseous Anaesthesia Devices:

Systems such as X-Tip and Stabident deliver anaesthetic directly into cancellous bone adjacent to the target tooth. They provide rapid onset and are useful when conventional mandibular blocks fail.

Needle-Free Jet Injection:

Jet injectors propel anaesthetic through the mucosa without a conventional needle. They reduce needle anxiety and may be useful for selected soft-tissue procedures and paediatric patients, although depth of anaesthesia can be limited.

Vibrotactile Devices:

Vibrotactile devices are based on the gate-control theory of pain, which proposes that simultaneous non-painful stimulation such as vibration or pressure can inhibit transmission of painful stimuli. Devices including VibraJect, DentalVibe, Accupal, and Buzzy apply vibration and, in some cases, cooling to the injection site before and during needle insertion. The 2025 review reported that DentalVibe and Buzzy demonstrated meaningful reductions in pain perception and anxiety in several paediatric studies, whereas VibraJect showed mixed clinical results. Because these devices are inexpensive, portable, and easy to integrate into routine practice, they are particularly valuable for anxious adults and children. However, evidence quality remains limited because many published trials involve small sample sizes and moderate risk of bias.

Figure 4. Vibrotactile pain modulation

Intraosseous Anaesthesia Systems:

Intraosseous anaesthesia delivers local anaesthetic directly into the cancellous bone adjacent to the target tooth. Systems such as Stabident, X-Tip, and IntraFlow are designed to overcome failures of conventional mandibular nerve blocks, particularly in teeth with irreversible pulpitis. These devices provide rapid onset, high pulpal anaesthesia success, and reduced need for supplemental injections. Stabident requires a separate perforation of cortical bone followed by needle placement into the perforation site, whereas X-Tip leaves a guiding sleeve in place to facilitate injection. IntraFlow combines perforation and anaesthetic delivery into a single continuous procedure.

The reviewed literature indicates that intraosseous systems are especially useful for posterior mandibular teeth and difficult endodontic cases, although equipment cost and operator training remain limitations.

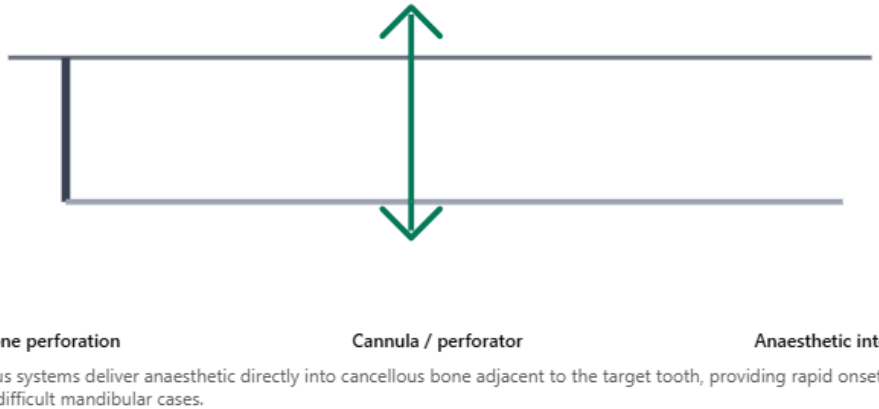


Figure 5. Intraosseous anaesthesia pathway

Needle-Free Jet Injection Systems:

Jet injection technology uses high-pressure mechanical energy to propel anaesthetic solution through the mucosa without a conventional needle. Devices such as Syrijet and MED-JET create a fine stream of anaesthetic that penetrates soft tissue and deposits solution into submucosal tissues. Needle-free systems reduce needle anxiety, eliminate needle-stick injuries, and provide rapid superficial anaesthesia. However, evidence for deep pulpal anaesthesia remains limited, and most studies suggest that jet injectors are more suitable as adjuncts for soft tissue procedures or as pre-injection anaesthesia rather than replacements for conventional infiltration or nerve block techniques

Buffered Local Anaesthesia:

Buffered local anaesthesia involves alkalinization of anaesthetic cartridges immediately before injection, typically by adding sodium bicarbonate. Increasing the pH of the solution increases the proportion of the non-ionized base form of the anaesthetic, resulting in faster diffusion across nerve membranes. Clinical studies have demonstrated reduced burning sensation during injection, faster onset of pulpal anaesthesia, and improved patient comfort in selected procedures. Buffered articaine and lidocaine are increasingly considered for procedures requiring rapid onset and predictable anaesthetic success. Chairside buffering systems have made this technique clinically practical.

More than only technical performance determines whether or not innovative dental anesthesia technology is clinically adopted. Infection control measures, staff education, workflow integration, patient approval, consumable costs, and equipment upkeep are additional factors to think about. Traditional syringes are still popular due to their inexpensive price and familiarity with use. On the other hand, computer-controlled systems necessitate the purchase of electrical devices and replaceable parts.

So, introducing cutting-edge innovation gradually is a realistic approach to implementation. CCLAD and STA devices may be more useful for high-volume clinics that handle worried patients, youngsters, complicated endodontic situations, or patients who need numerous localized operations. In endodontic practices, where traditional mandibular anesthesia often fails, intraosseous devices could be a lifesaver.

Vibrotactile and Cryotherapy-Assisted Techniques

Vibrating devices reduce perceived pain through the gate-control theory of pain modulation. Pre-cooling the mucosa with ice or refrigerant sprays before injection can also reduce discomfort during needle penetration.

One principle that underpins vibrotactile technology is the idea of pain modulation thru gate control. As an alternative to nociceptive stimulation, non-painful sensory input, such as vibration, is provided close to the injection site. For this aim, devices like Buzzy, Accupal, VibraJect, and DentalVibe have been studied. Despite contradictory data among devices and studies, the uploaded paper shows encouraging improvements in pain perception and anxiety, especially among pediatric patients.

Fig.6 Vibrotactile technique

An further sensory-modulation mechanism can be provided by cryotherapy. To lessen the sensation of pain during needle insertion, it may be helpful to cool the mucous tissue beforehand to lessen local sensory perception. An intriguing multi modal strategy that aims to alter pain perception prior to the pharmacological nerve blockage generated by the local anesthetic is the combination of cooling and vibration.

One hand piece could one day combine vibration, cooling, lighting, and controlled injection. The clinical workflow could be made easier and fewer devices needed with such an integrated platform.

Electronic Dental Anaesthesia

Electronic dental anaesthesia (EDA) uses transcutaneous electrical nerve stimulation (TENS) or similar electrical stimulation systems to modulate pain perception. These devices provide analgesia by stimulating peripheral nerves and interfering with transmission of pain signals. EDA has demonstrated effectiveness in reducing discomfort

during certain dental procedures, particularly in children and needle-phobic patients. Nevertheless, its routine use remains limited because of variable efficacy, additional equipment requirements, and inconsistent clinical evidence compared with conventional local anaesthesia.

Electronic Dental Anaesthesia and Emerging Technologies

Electronic dental anaesthesia delivers low-level electrical stimulation to modulate pain perception. Artificial intelligence, digital treatment planning, and sensor-guided injection systems are emerging tools that may improve accuracy and safety.

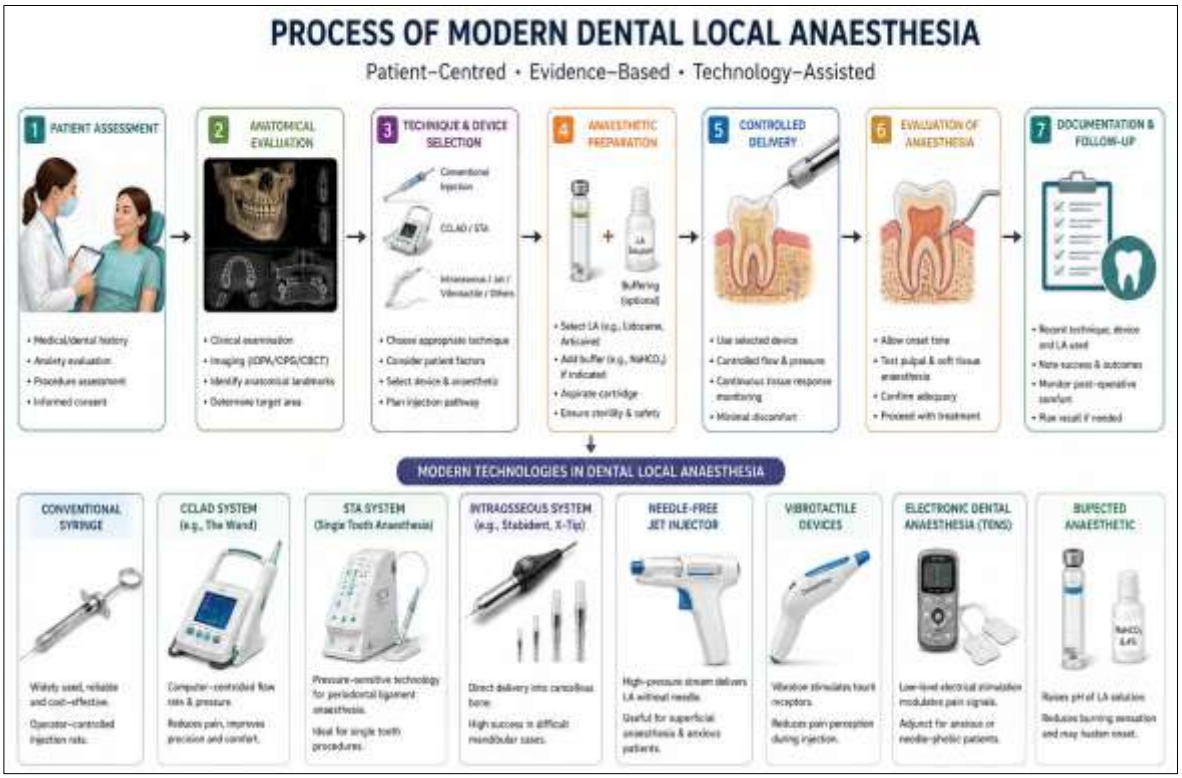


Fig.7 Block diagram of process

You can find non-pharmacological methods to alleviate pain and anxiety during dental local anesthetic injections, such as vibrotactile and cryotherapy-assisted treatments, in the figure. In order to alter the transmission of pain signals according to the gate-control paradigm, the vibrotactile approach applies a vibrating device near the injection site to stimulate large-diameter A-beta nerve fibers. In certain cases, such as with nervous patients or young children, the use of vibration before to and during needle penetration may alleviate pain and anxiety. Needle insertion may be less painful using cryotherapy-assisted anesthesia, which involves chilling specific areas before injection to temporarily lessen tissue sensitivity.

Comparative Analysis of Conventional and Modern Techniques

The following comparison summarizes the major differences between traditional syringe techniques and recent advances.

Parameter	Conventional syringe	Modern techniques/devices
Pain during injection	Moderate	Reduced
Injection precision	Operator dependent	High (CCLAD)
Onset of anaesthesia	Standard	Faster (buffered/IOA)
Patient anxiety	Higher	Lower (vibrotactile/jet)
Mandibular block failure management	Limited	Improved (IOA)
Equipment cost	Low	Moderate to high
Training requirement	Minimal	Additional training

Overall, CCLAD systems demonstrate the strongest evidence for reducing injection discomfort, while intraosseous anaesthesia offers the greatest benefit for difficult mandibular cases. Vibrotactile devices and buffered anaesthesia improve patient comfort but require further high-quality randomized clinical trials.

Advantages

Recent advances provide improved patient comfort, reduced anxiety, faster onset, enhanced precision, better anaesthetic success in difficult cases, and greater acceptance of dental treatment.

Current evidence suggests that CCLAD is the most advanced method for making injections more comfortable. A randomized-trial systematic review in 2024 found that computer-assisted delivery reduced pain perception and improved patient behavior, and a pediatric meta-analysis in 2025 found that there were statistically significant reductions in pain-related outcomes. Intraosseous techniques are a useful supplementary method for challenging mandibular cases, and other technologies like cooling, buffering, vibration, and needle-free systems are supportive.

LIMITATIONS

Limitations include device cost, learning curve, maintenance requirements, availability, and limited evidence for some newer technologies.

Dental local anesthesia has come a long way, but there are still a few things holding it back from being used more frequently in clinical settings. Because of the specific nature and one-time use nature of the components needed for intraosseous systems, computer-controlled local anesthetic delivery (CCLAD), and single tooth anesthesia (STA), the associated equipment can be quite expensive. Because doctors need to know how to operate the device, how to manage the pressure, where to place the needle, and what clinical indications are appropriate, more operator training is required. Cost, learning curve, maintenance needs, restricted availability, and extra training are listed as important drawbacks in the uploaded paper.

FUTURE DIRECTIONS

Future developments are expected to include AI-assisted injection guidance, robotic delivery systems, smart cartridges with pressure monitoring, and personalized anaesthetic protocols based on patient-specific anatomy and pharmacogenomics.

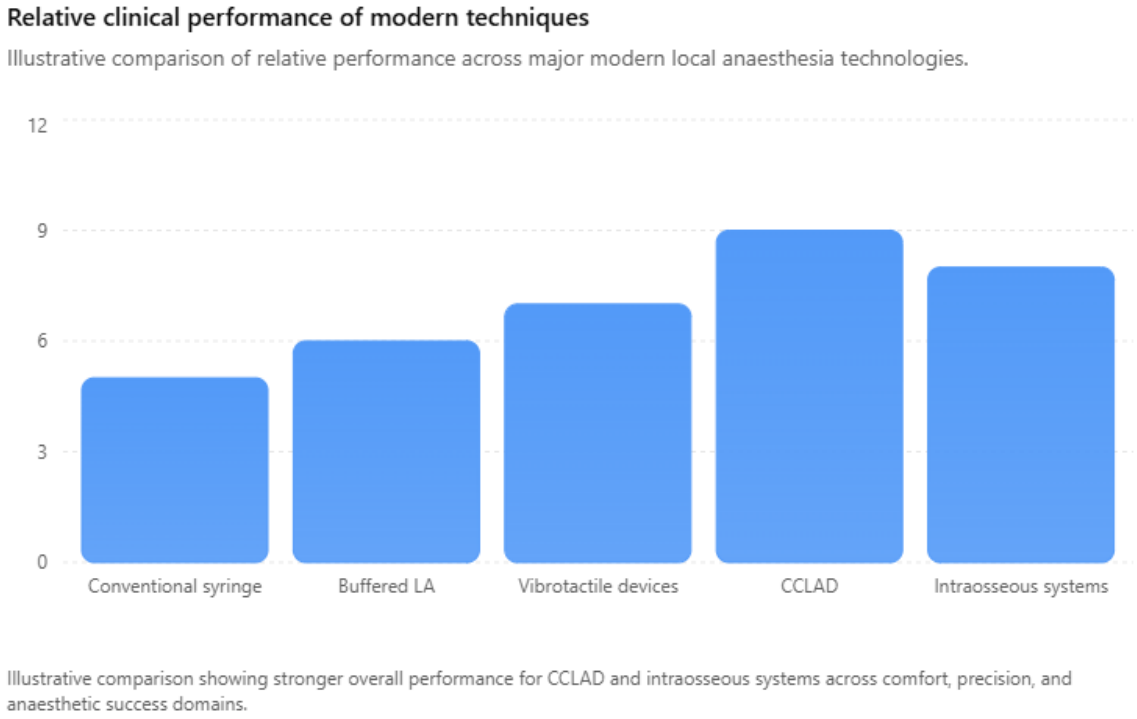


Figure 8. Relative clinical performance of modern techniques

Future developments in dental local anaesthesia are expected to integrate digital technologies, artificial intelligence, and minimally invasive delivery systems. Potential innovations include AI-assisted injection

guidance, robotic syringe control, pressure-sensing smart cartridges, image-guided anaesthetic delivery, personalized anaesthetic protocols based on patient-specific anatomy and pharmacogenomics, and microneedle or needleless trans-mucosal delivery systems. Digital workflows may eventually allow real-time mapping of neural anatomy and automated optimization of injection depth, angle, and volume, thereby improving safety and reducing anaesthetic failure.

CONCLUSION

Beyond just alleviating pain, these advancements are significant. Patients are more likely to cooperate, have less dental fear, finish their treatments more quickly, and even be more ready to go to the dentist again if they had a more pleasant anesthetic experience. Childhood dental phobia can have a lasting impact on children's attitudes toward dental care, therefore it's crucial that they learn to relax when getting injections.

Dental local anaesthesia has progressed from conventional syringe techniques to digitally assisted and minimally invasive delivery systems. Buffered anaesthetics, CCLAD devices, intraosseous systems, and digital technologies represent important advances that can improve comfort and clinical outcomes. Continued research and clinician training will determine their broader integration into routine dental practice. Dental local anaesthesia has progressed from conventional manual syringe techniques to sophisticated computer-assisted and minimally invasive delivery systems. Computer-controlled local anaesthetic delivery systems, Single Tooth Anaesthesia, intraosseous anaesthesia devices, vibrotactile technologies, jet injectors, buffered local anaesthesia, and digital guidance systems represent major advances aimed at reducing pain, anxiety, and anaesthetic failure. Current evidence indicates that CCLAD provides the most consistent reduction in injection discomfort, while intraosseous systems improve success in difficult mandibular cases. Vibrotactile and buffered techniques offer additional benefits for patient comfort and rapid onset, although further high-quality randomized clinical trials are required. The future of dental anaesthesia is likely to be characterized by digital integration, artificial intelligence-assisted injection guidance, and personalized anaesthetic delivery protocols that maximize comfort, precision, and clinical predictability.

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