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Laser Analgesia with Pulsed Infrared Lasers: Theory and Practice

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Abstract: Over the past decade, the use of middle infrared (Er:YAG and Er,Cr:YSGG) lasers for caries removal and cavity preparation has become commonplace in clinical practice. These lasers are also being used increasingly for soft tissue surgery and for hard-tissue crown lengthening surgery. This paper addresses possible mechanisms that may contribute to a positive patient experience with reduced need for injected local anaesthesia during restorative dentistry when performed with lasers, and then focuses on the concept of laser-induced analgesia as a low-level effect which contributes to the reduced discomfort experienced by dental patients when pulsed middle infrared lasers (Nd:YAG as well as Er:YAG and Er,Cr:YSGG) are employed.

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A major advantage of pulsed infrared lasers when used on dental hard tissues is the reduced nociceptive (pain) response compared with conventional instruments such as air turbine drills. These lasers provide the clinician with the ability to work more conservatively, and in different quadrants at the same appointment, with a greatly reduced need for injected local anaesthesia.[1,2] Overall, this facilitates a minimalist philosophy, and reduces stress for both patients and clinical operators.[3] A number of possible mechanisms may contribute to the positive patient experience during restorative dentistry when performed with lasers (Table 1), and these are most likely additive in nature rather than being mutually exclusive.

Table 1 Possible mechanisms in reduced patient responsiveness during laser treatment with pulsed infrared lasers

Lower annoyance factor
Lowered patient anxiety
Elevated pain threshold
Short pulse duration
Lack of tactile force
Reduced pulp temperature
Shock waves inducing gate control
Shock waves reducing nerve transmission

Lower annoyance factor

The term "annoyance factor" summarizes a patient's subjective reaction to operative dentistry procedures, such as caries removal and cavity preparation.[1,4] The annoyance factor is a combination of the pressure applied to the tooth, the vibrations and noise recorded through the bones of the skull, the heat and smell generated at the interface between the tooth and the cutting instrument, and the time taken to perform the task. The annoyance factor of pulsed middle infrared lasers is low compared with rotary instruments, for which vibration and noise generation are well known characteristics disliked by dental patients.[4] The generation of frictional heat and the smell of partially burnt tooth structure when coolant flow is inadequate are also issues for dental patients.

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Careful investigation of both the amplitude and frequency of vibrations induced by air turbine instrumentation compared with cavity preparation laser procedures reveals that the total sensory input is much less with lasers.[5] When the Er:YAG laser is used on teeth at pulse energies up to 350 mJ, only a small amount of tooth vibration occurs compared with the air turbine handpiece, and there is a much lower mean frequency (230 Hz vs 5 kHz, respectively). The air turbine causes greater tooth vibration, and has a frequency spectrum near the upper end of the audible spectrum, giving the characteristic "whine" which evokes anxiety during tooth preparation. Bearing in mind the perspective of the patient who is about to have a tooth treated, the downstream effects of laser therapy – less anxiety-inducing stimuli and thus less anxiety (and therefore higher pain thresholds) – need to be considered.

Altered patient responses

When the processes for effective cutting of tooth structure using pulsed infrared lasers were being developed, many investigations noted a dramatic lack of adverse effects in terms of perceived discomfort, even when injected local anaesthesia was not used.[6-12] In a seminal study by Cozen et al,[7] data provided to the United States Food and Drug Administration to support clinical use of the Er:YAG laser for cavity preparation showed that less than 2% of patients required local anaesthesia, and that hard tissue treatment was safe in terms of effects on the dental pulp. In another landmark study conducted by Hibst et al,[6] during restorative treatment of 103 patients (206 cavity preparations), the need for injected local anaesthesia was only 6% for laser therapy, with 74% of patients rating laser preparation as "comfortable" overall, and 80% of patients rating the conventional preparation as more uncomfortable than laser treatment. Some 50% of patients rated laser treatment in a category with higher comfort than conventional treatment of a similar cavity. All patients who requested local anaesthesia during laser preparation also required local anaesthesia during mechanical cavity preparation. Interestingly, in that study, laser preparation of palatal, lingual, mesial, and distal regions was rated as comfortable in 90% of cases, while for the buccal and the occlusal sites the corresponding frequency was much lower at 63% and 69%, respectively. As will be discussed later in this paper, this site difference is consistent with a mechanism based on pulse transmission from the site of laser impact, across the dentine to the dental pulp.

Does irreversible damage to pulpal nerves occur?

A possible interpretation of the reduced discomfort during laser treatment which has been suggested in the literature is that pulpal nerves are being affected in a way which caused their irreversible damage and eventual loss from photothermal effects. However, published data do not support such a mechanism. For instance, higher pulpal temperatures would have resulted in greater discomfort rather than reduced pain sensations during treatment. In addition, in the early clinical trials of laser caries therapy, vitality of all teeth after laser preparation was found, confirming that cavity preparation with the Er:YAG laser is a safe procedure.[6-12] Moreover, in a number of clinical trials involving treatment of teeth destined for extraction for orthodontic purposes, no evidence of histological or biochemical injury to the dental pulp from laser cavity preparation was found.[13-14] Parallel positive results with a lack of pulpal injury have been reported with the Nd:YAG laser when used in pulsed mode, either to desensitize exposed dentine or to assist with analgesia during caries treatment.[15-18] Thus, the fact that patients have been routinely treated without local anaesthesia, and experience little or no discomfort during cavity preparation, is not due to degenerative or inflammatory processes involving the dental pulp.

Photothermal effects accompanying cavity preparation, and their consequences

With Er:YAG and Er,Cr:YSGG lasers, absorption of laser energy within inter-crystalline water in enamel and dentine causes an explosive subsurface expansion of this interstitially trapped water, resulting in rapid ejection of apatite crystals in the opposite direction from the incoming laser beam.[1] As carious tooth structure contains more water than sound tooth structure, the former can be removed selectively because of its lower ablation threshold and greater ablation rates at low pulse energies. The process of ablation was described in detail in 1988 by Hibst et al,[19-20] who demonstrated that the Er:YAG laser could remove caries with minimal thermal effects in the adjacent hard and soft tissues.

Of note, the evaporation of the water creates a cooling effect, and this mitigates against the inherently thermal nature of the process. In fact, erbium-based laser systems can achieve effective ablation at temperatures well below the melting and vapourization temperatures of enamel. These lasers routinely use a water

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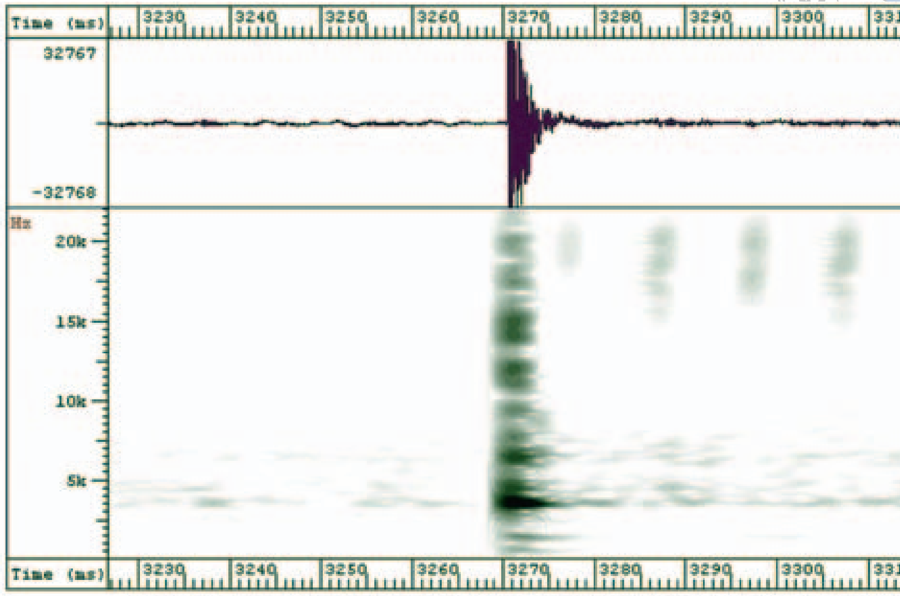

Fig 1 Waveform recorded from a single 300 mJ pulse from an Er:YAG laser which has passed through sound dentine. There is a large content in the high frequency portion of the audible spectrum (shown on the vertical axis). The intensity falls away rapidly with time (shown in milliseconds on the horizontal axis).

mist spray to ensure effective energy coupling of the applied laser energy. This spray also assists in cooling the target between pulses. A net negative thermodynamic change (cooling) has been documented during laser cavity preparation; this reduction in temperature may contribute to a reduced response from nociceptors in the dental pulp.[13]

Lack of direct pressure and tactile force

Part of the positive patient experience of laser cavity preparation may be due to the lack of physical force applied to the tooth. Unlike rotary instruments, where both apically and laterally directed forces are applied through rotary instruments to the teeth (and therefore transmitted to pressure receptors in the periodontal ligament), laser cavity preparation does not involve use of significant force. A variety of handpieces are used to deliver pulsed erbium laser energy, ranging from non-contact window handpieces to straight and curved optical (quartz or sapphire) tips, which are applied close to the tooth surface, but rarely touching it.

Photoacoustic effects and gate control

On hard tissues, the generation of laser-induced shock waves (or stress waves) is a well-recognized phenomenon.[21] A variety of photo-acoustic effects occur during erbium laser cavity preparation, and these may be significant contributors to a laser-induced analgesic effect, as will be discussed further below. Small shock waves traverse lased tooth structure, and can therefore interact with the dental pulp. These shock waves arise from the volume expansion of rapidly heated water. Their characteristics are influenced by several factors including the speed of sound in the tissue, the tissue density, and the pulse duration. From the standpoint of acoustics, because the shock waves arise from an explosion with ejection of material from the tooth (and accompanying ablative recoil), there is little amplitude (audible loudness) until the ablation threshold is reached. Above the ablation threshold, the loudness increases as more and more ejection of material occurs. This is why erbium-based laser systems produce a characteristic popping sound when the laser is operating on dental hard tissues at pulse energies above the ablation threshold.

In terms of both the human ear response and the response generated within the dental pulp, both the pitch and resonance of this sound relate to the propagation of an acoustic shock wave. The small shock waves traversing the dentine and reaching the pulp can be recorded using miniature surface contact microphones. Analysis of these waves reveals that healthy tooth structure produces a "click" sound because the waveform has some high frequency content and a rapid decay over time (Fig 1), while the reduced tissue density of carious tooth structure gives the traversing

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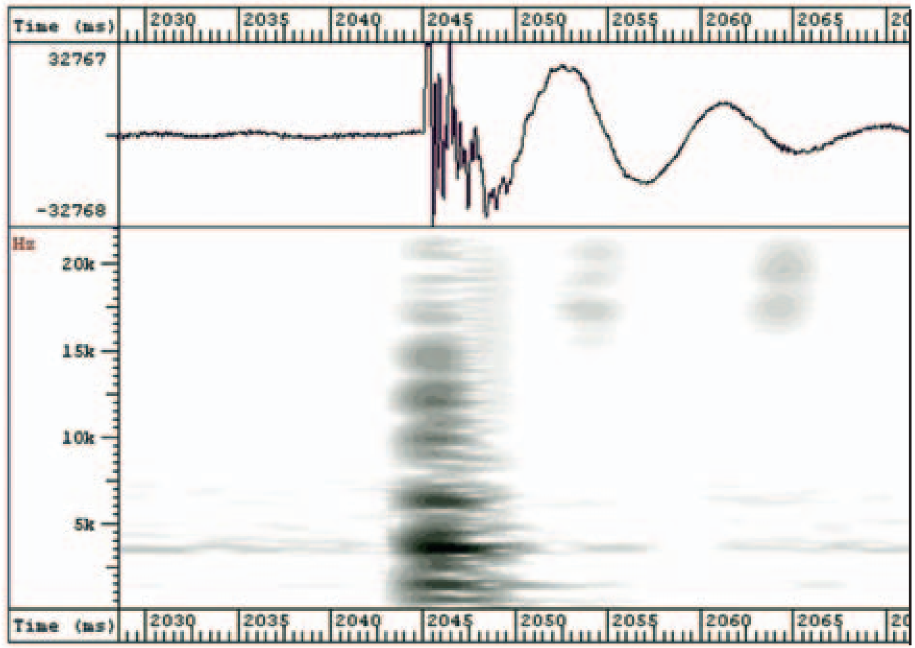

Fig 2 Waveform recorded from a single 300 mJ Er:YAG laser pulse which has passed through carious dentine. Note the large content in the low frequency portion of the audible spectrum, and the long decay of the pulse over time, compared with Fig 1.

waveform a "thud" sound because of its stronger low frequency content and slow decay over time (Fig 2). These waves, upon reaching the pulp, may cause pressure fluctuations within the dental pulp tissue, giving rise to a sensation of "small earthquakes". This proprioceptive input to the nervous system, if of sufficient intensity, could potentially induce a dampening of responses through the gate control pathway. The gate control mechanism is based on the concept that the sensory nervous system at its lower levels senses vibrations first, and then cannot transmit feelings of pain (nociception). Thus, a barrage of vibrations or laser-induced shock waves could essentially mask any underlying discomfort.

A direct analgesic action?

Many patients undergoing cavity preparation with erbium lasers do not need injected local anaesthesia, and most large scale clinical trials report that only 2% to 6% of patients will request or require local anaesthesia.[6-12] Given the events accompanying the laser pulses that have been described above, it is self-evident that many patients may experience slight, intermittent sensations of coolness with each pulse (from the cooling effects of water evaporation), and subtle "earthquake" sensations from shock waves. While rather different from the experience of traditional restorative dentistry, these are not perceived as unpleasant. Younger patients with large, rapidly progressive carious lesions in previously unfilled teeth (and thus little secondary dentine) tend to notice these sensations more than older adults whose teeth have thicker and less porous dentine (from age and from previous restorations). Many patients, however, have virtually no sensation whatsoever during lasing.[1,2]

There is an intriguing possibility that there is a direct analgesic effect created by laser treatment which operates by reversibly blocking nerve transmission. As a device which generates a vibrational action through a photoacoustic effect, the similarity between vibrations induced by lasing and those induced by mechanical means is important to consider. Mechanical vibrations have been known to induce paraesthesia in human tissues, the classic example being vibrating hand tools which cause numbness to develop in the hand after these have been used for a short time by a worker. One device, the Vibraject™, has been developed to reduce pain during dental injections, and provides a low intensity mechanical vibration to a local anaesthetic needle at a frequency of some 20 Hz, using a miniature transducer powered by batteries. The effect of vibrating hand tools and the Vibraject could be largely due to

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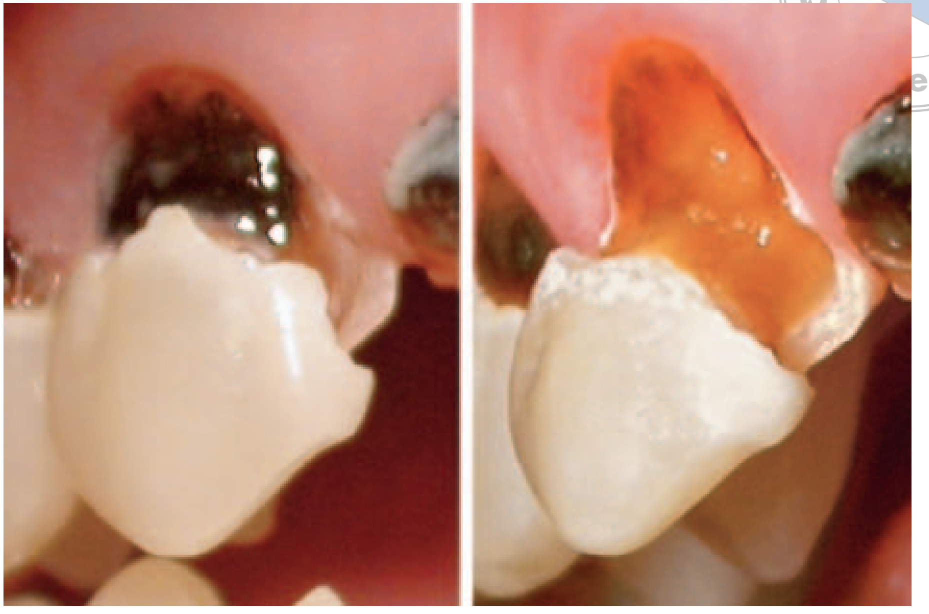

Fig 3 Before and after images of anaesthesia-free Er:YAG laser treatment of a canine tooth with deep caries in a young dentally phobic patient, including gingivoplasty, caries removal and etching. From Ref. 2, with permission.

gate control; however, a direct contribution of shock waves and vibration per se to reduced responsiveness is possible.

While a large body of work has already established that short-wavelength (810 to 830 nm) near-infrared laser radiation can suppress nerve firing,[22-31] this effect appears to be quantitatively and qualitatively somewhat different from that seen with the longer infrared wavelengths from the Nd:YAG and erbium lasers. Early work in the 1990s with free-running pulsed Nd:YAG lasers showed that pulsed laser radiation could penetrate dentine and reach the pulp, and was responsible for part of the desensitizing effect of this laser when applied to cervical dentine. Another part of the desensitizing effect was due to a partial occlusion of dentinal tubules.[32-36] Similar effects were seen with Er:YAG lasers, where both surface and pulpal actions appeared involved in the desensitizing action.[37,38]

Subsequent studies of laser-induced analgesia with the free-running pulsed Nd:YAG and Er:YAG lasers by the Orchardson and Zeredo groups, respectively, using rodents showed conclusively that a dramatic blockage of neuronal activity and a corresponding increase in the pain threshold of teeth did occur after laser irradiation.[39-46] These animal studies are particularly informative, since they show data for intradental nerve electrical activity after standardized stimuli have been applied. The laser-induced analgesic effect in these studies had a clear dose response for its onset, and declined after 15 to 20 minutes. Of interest, it was also associated with the blockade of late-phase neurogenic inflammation (which is driven by the effects of neuropeptides). Analgesic mechanisms associated with infrared lasers have been attributed to inhibited release of inflammatory mediators,[47-49] as well as blocked depolarization of nociceptive afferents,[42,50,51] with the former playing a role in the suppression of late phase neurogenic inflammation.

The analgesic effects seen in animal models are qualitatively similar to those which occur in clinical practice when preparing cavities with Er:YAG and Er,Cr:YSGG lasers,[1,2,52] or when using Nd:YAG lasers for desensitizing, laser analgesia or caries therapy. The design of the animal studies, however, removes all possibility of placebo effects and psychogenic influences. Most importantly, this sizeable body of work demonstrates that there is a fundamental reversible alteration in the nociceptive response caused by laser treatment, which suppresses nerve firing for a given level of stimulus.

Clinically, the blockade generated with shorter exposures (30 s) is more selective for depolarization of A delta fibers (which give rise to sensations of rapid, sharp, well-localized pain) than for C fibers, which explains why some patients notice during laser treatment low level shock waves ("mini-earthquakes"), but do not experience discomfort. Laser analgesia is known to be induced at subablative settings, which allow penetration of both teeth and soft tissues (eg, through to the

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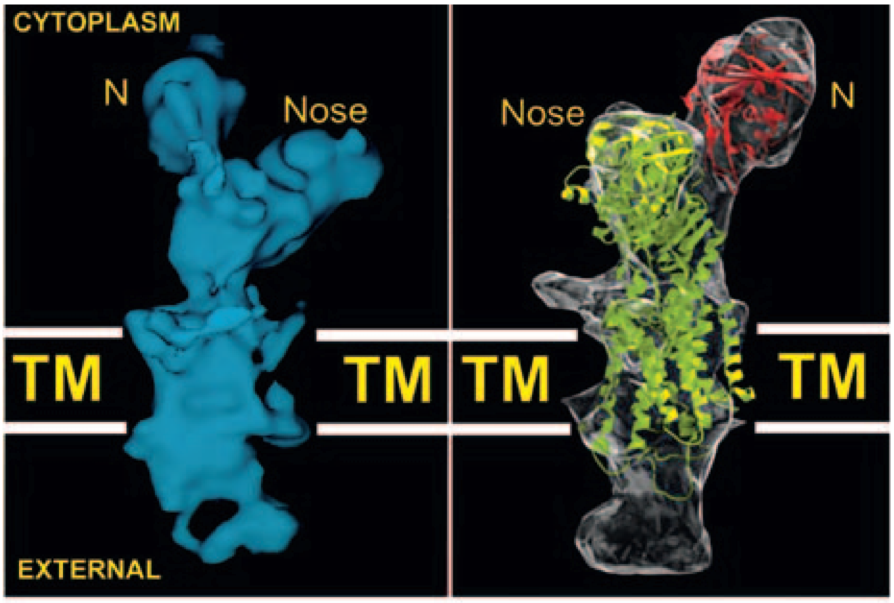

Fig 4 Structure of the NaK transmembrane pump, based on molecular modeling and X-ray crystallographic studies. The pump has external, transmembrane (TM) and inner cytoplasmic parts, and a controlling beta domain (N). Vibrational effects are thought to act at the interface of the beta domain and the cytoplasmic "nose", closing the pump's inner channel and thereby blocking membrane repolarization. From Ref. 2, with permission.

pulp via the attached gingiva and labial alveolar bone). Because of some persisting C fiber activity, some patients notice cooling effects in their teeth during lasing due to evaporative energy loss (the thermodynamics dictate that with a net energy loss, pulpal cooling of up to 7°C may occur). As noted earlier, these mild sensations would be more likely to occur in younger patients, and in previously unrestored teeth with rapidly progressive caries on the buccal surfaces of canine and premolar teeth, as these have the shortest, straightest, and widest dentine tubules in adult patients, and the least secondary dentine (Fig 3). Achieving reliable laser analgesia as a pre-emptive step in such cases involves using the lower energies and higher pulse frequencies, which give the penetrating analgesic effect rather than surface ablation of tooth structure.

Since microscopic studies on both animals and humans have shown the laser-induced analgesia effect is molecular rather than histological in nature, the issue then arises of the targets involved. The work of Orchardson and colleagues has shown that pulsed infrared (Nd:YAG and Er:YAG) laser treatment of nerves blocks nerve conduction,[39-41] indicating that a direct effect of laser pulses on neural tissue may be an important mechanism. With the Nd:YAG laser, Orchardson's group also showed that lasing in pulsed mode (10 to 30 Hz) depressed intradental nerve responses to dentine stimuli in the canine teeth of anaesthetized ferrets.[53] This validated human clinical studies of the same phenomenon, albeit applied in humans in clinical dental practice in restorative dentistry.[35,54]

Clinically, it can be observed that changing the frequency of pulsing the laser alters the analgesic action, which suggests that a resonance effect is occurring (eg, with an optimal frequency near 20 Hz). The putative target for a photo-acoustic effect is the Na/K ATPase pump. This pump generates Na+ and K+ gradients across the plasma membrane in virtually all animal cells, and is particularly important in nerves for re-establishing membrane polarity after transmission of impulses. During one enzymatic cycle, the pump transports three Na+ ions out of the cell and two K+ ions into the cell, while hydrolyzing one molecule of ATP.[55] The cytoplasmic head is subdivided into three parts: the nose, and P- and N-domains. The configuration of the subunits and various domains of the pump is critical for its proper folding in three dimensions and therefore its function.

The x-ray crystallographic work of Rice and colleagues[55,56] has shown that this pump is a hollow tubular protein which spans the cell membrane of nerves, and establishes the gradients in sodium and potassium which are essential for propagating an impulse down a nerve through membrane depolarization and repolarization. Partial spatial dissociation of the beta domain of this ion channel protein (which controls its function) closes the lumen of the "pipe" and thus prevents repolarization for a short period of time[2] (Fig 4). When

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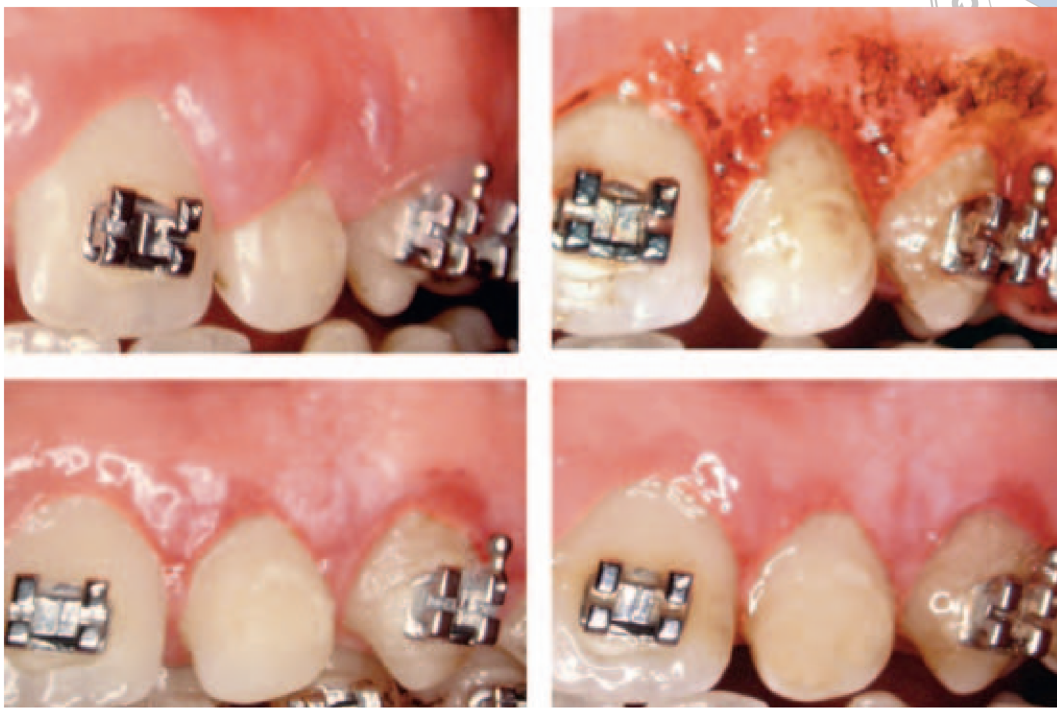

Fig 5 Anaesthesia-free gingivoplasty undertaken with water mist spray to uncover buccal tooth surfaces affected by gingival overgrowth during orthodontic treatment. The patient did not undertake mechanical oral hygiene or use any mouthrinses during the 2 week post-surgical period. From Ref. 2, with permission.

this spatial change is caused by vibrational energy, the phenomenon has been termed "bioresonance".

Clinical applications of laser-induced analgesia

Deliberate "pre-emptive" analgesia, that is, analgesia at the start of a procedure, can be created by applying subablative laser pulses to the crowns of teeth. The energy should be directed at the cementoenamel junction, towards the dental pulp, through the enamel or dentine. Alternatively, energy can be applied to root apices (ie, through the buccal gingiva and alveolar bone). To achieve effective analgesia, use of subablative pulse energies and an appropriate frequency are essential. Typical parameters for erbium lasers are 60 to 120 mJ/pulse (defocused, with water spray), at a frequency between 10 to 30 Hz (preferably 20 Hz), applied for at least 30 s. Ideally, energy should be applied at each of the four line angles of a tooth. The optimal effect is gained at a pulse frequency of 20 Hz, which appears to align with the resonance frequency needed to temporarily disrupt the action of the Na/K pump. Moving the laser handpiece in a sweeping action at approximately 2 to 3 mm/s during the 20- to 30-s period at each line angle distributes the effect evenly across the dental pulp.

Using the above protocol, one series of exposures would normally give sufficient analgesic effect to allow for removal of an amalgam restoration using an air turbine handpiece (prior to then removing recurrent caries with the laser). Infrared laser radiation will not pass through, but will absorb in dental amalgam, and thus dental amalgam should not be lased. The same is true for composite resin restorations which may be present at the cementoenamel junction of teeth – these should not be lased directly if analgesia is intended. With an Nd:YAG laser, appropriate parameters are 50 to 100 mJ/pulse (defocused, without water spray), at a frequency of 20 Hz, once again applied for 30 s at each of the line angles.

The development of an effective laser analgesic effect can be significant for patient comfort, allowing minimal intervention treatment in several teeth, in one appointment, without the need for injected local anaesthesia. The suppressive effects of pulsed infrared laser energy on nerve firing may lead to an analgesic effect with a duration clinically of some 10 to 15 min. While this is sufficient for straightforward restorative procedures, the effect can, if needed, be sustained or induced again by further lasing.

If discomfort occurs during caries removal and cavity preparation, the likely causes and related actions are as follows:

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1. Inadequate laser-induced analgesia: increase the pulse frequency to 20 Hz whilst simultaneously reducing the pulse energy (power) or defocussing. Develop the analgesic effect by working from the cavity margins inwards in a spiral motion, directing the energy towards the pulp.
2. Thermal effects on the dental pulp: check that the water spray rate is sufficient. Keep the suction/high velocity evacuator tip away from the laser handpiece water-spray jets.
3. Dehydration of the dentine: keep the suction/high velocity evacuator tip away from the tooth. Apply a lining material such as glass-ionomer cement to the dentine to prevent water loss. This type of dentinal pain is mediated by a hydrodynamic mechanism, and occurs because of the open tubules and lack of a smear layer which characterizes lased dentine. Drying and evaporation both stimulate fluid to flow away from the pulp, and activate intradental nerves.[57]

Soft tissue procedures

Using water mist spray to couple the vibrational action of laser energy into oral soft tissues, laser-induced analgesia can be exploited for some types of soft tissue procedures, as well as for cavity preparation. Recent animal studies by Zeredo's group have confirmed that Er:YAG laser incisions to lip, gingiva, mucosa, and tongue are less painful than with scalpel, when both are undertaken without local anaesthesia,[44,45] scientifically validating clinical situations where minor procedures such as gingivoplasty during cavity preparation can be undertaken in conjunction with water mist spray without causing patient discomfort (Fig 5). Although anesthesia is mandatory for conventional scalpel surgery, Aoki et al[58] were able to treat 61 patients with a variety of surgical procedures, such as gingivectomy and frenectomy, under no infiltrative anesthesia. In that study, the patients' subjective pain assessment using a visual analogue scale ranged only from slight to moderate.

Gingivoplasty procedures with pulsed middle infrared lasers can of course be undertaken for reasons unrelated to restorative dentistry, such as during or following orthodontic treatment (Fig 5). For such procedures, higher water flow rates should be used compared with cavity preparation, both to ensure sufficient cooling and to couple vibrational energy into the oral soft tissues.

CONCLUSIONS

Laser-induced analgesia likely results from the combination of a local bioresonance effect which blocks nerve impulse transmissions from some nociceptors, in combination with some gate control, and centrally with altered patient responses from reduced levels of anxiety. The applications of pre-emptive analgesia for caries removal and cavity preparation have contributed to the positive results seen when middle infrared lasers are used. Several current commercial systems include preset parameters for laser analgesia, which are based on the work described in this paper. The application of analgesic approaches for soft-tissue surgery procedures offers hope for even greater deployment of laser technology in general dental practice settings.

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