Laser-Assisted Endodontics

Roy George and Laurence J. Walsh

D.J. Coluzzi, S. Parker (eds.), *Lasers in Dentistry—Current Concepts*, Textbooks in Contemporary Dentistry,
DOI 10.1007/978-3-319-51944-9_9

Core Message
Conventional endodontic treatment relies on mechanically preparing the root canal space with either hand or rotary instrument prior to disinfecting a three dimensionally complex anatomical root space with irrigants and medicament. This painstakingly slow treatment process is further complicated by the inability to assess the quality of disinfection achieved in the root space. The use of lasers can assist in providing enhanced detection of bacteria and microbial biofilms in the root canal, to guide debridement approaches and help define endpoints for instrumentation. Fluorescence feedback can indicate where microbial deposits remain and where further treatment is needed. Further, there are a range of ways that lasers can enhance biomechanical preparation of the root canal system, particularly through fluid agitation and inducing cavitation in water-based fluids, to remove debris and smear layers. Such actions can be optimized using modified laser fibers tips to deliver the laser energy in various side-firing patterns. Lasers can achieve disinfection of the root canal through both photothermal and photodynamic processes, reaching areas that are difficult to access using conventional instrumentation and irrigating techniques. Additional applications of lasers in endodontics include the assessment of pulp vitality through laser Doppler flowmetry, photothermal and photodynamic bleaching of discolored sclerosed vital or stained nonvital teeth, pulp capping and pulpotomy, photobiomodulation and laser-induced analgesia, and endodontic surgical applications including periapical surgery and treatment of invasive cervical resorption. In each of these areas, the use of lasers can simplify treatment protocols and optimize clinical outcomes.

9

9.1 Introduction

The primary goal of root canal treatment is to eliminate microorganisms from the root canal system and radicular dentin. Laser technology can assist in the diagnosis of microbial deposits to guide biomechanical treatments and can help to inactive organisms through a range of thermal, photodynamic, and photomechanical processes. Unlike mechanical instrumentation such as hand or rotary endodontic files, laser effects reach across the entire root canal system and penetrate to some extent into dentin tubules. It is well known that with conventional instrumentation, large parts of the root canal system are untouched. The use of lasers, in many cases combined with appropriate fluids, can assist in achieving the goals of three-dimensional cleaning and profound disinfection of the canal.

Supporting these primary goals of endodontics are other laser applications in the diagnostic and therapeutic categories, as shown in ◘ Table 9.1. The uses of various lasers used in endodontics and some of their more popular applications are listed in ◘ Table 9.2.

◘ **Table 9.1** Classification of uses of lasers in endodontics

Primary application	Examples
Diagnosis	Detection of pulp vitality Doppler flowmetry Low-level laser therapy (LLLT) Laser fluorescence Detection of bacteria
Pulp therapy	Pulp capping Pulpotomy
Canal preparation	Biomechanical preparation Removal of smear layer Sterilization of the root canal High-level lasers – photothermal disinfection Low-level lasers –photodynamic disinfection
Periapical surgery	Ablation of granulation tissue Bone cutting and root resection
Laser photobiomodulation	Laser-induced analgesia Accelerated healing after pulpotomy or periapical surgery
Other	Removal of root canal filling materials and fractured instrument Softening gutta-percha Removal of moisture/drying of canal

9.2 Diagnostic Laser Applications

9.2.1 Laser Doppler Flowmetry

During dental pulp sensibility testing, a pain response elicited to a hot or cold stimulus or to an electric pulp tester provides information about the dental pulpal sensory supply, but not about its blood supply. Although the sensitivity of these commonly used tests is high, false results can lead to unnecessary endodontic treatment. This is a particular problem when teeth have experienced dental trauma or are undergoing orthodontic tooth movement [1].

In laser Doppler flowmetry (LDF), laser light is transmitted through tooth structure to the dental pulp by means of a fiber optic probe held in a reproducible position on the tooth surface. If the pulp is vital, there will be blood flow within the tissue. With movement of erythrocytes, the scattered light is frequency-shifted, whilst light reflected from static tissue is un-shifted. The reflected light is analyzed for its frequency shift to give a noninvasive, objective, painless, semi-quantitative assessment of pulpal blood flow. LDF has been used to estimating pulpal vitality in both adults and children, particularly in teeth which have been affected by dental trauma, excessive occlusal forces or orthodontic movement.

Table 9.2 Selected applications of lasers

Laser	Wavelength	Reported uses in endodontics
Short wavelength	Argon 488–514.5 nm	Endodontic disinfection
	KTP 532 nm	Soft tissue surgery in endodontics, endodontic disinfection
	He-Ne 633 nm Diode 635 nm	Doppler flowmetry, photoactivated disinfection of root canals
	Diode 810–980 nm	Soft tissue surgery in endodontics, endodontic disinfection, laser-induced analgesia, laser photobiomodulation
	Nd:YAG 1064 nm	Soft tissue surgery in endodontics, endodontic disinfection, biomechanical preparation
Long wavelength	Ho:YAG 2100 nm	Tooth preparation, soft and hard tissue surgery in endodontics, endodontic disinfection, biomechanical preparation
	Er,Cr:YSGG 2780 nm	Tooth preparation, soft and hard tissue surgery in endodontics, endodontic disinfection, biomechanical preparation
	Er:YAG 2940 nm	Tooth preparation, soft and hard tissue surgery in endodontics, endodontic disinfection, biomechanical preparation
	Carbon dioxide 10,600 nm	Pulp capping; soft tissue surgery in endodontics

LDF can also assist in the recognition of nonvital teeth. For this application, LDF has been found to be particularly valuable for assessing the blood flow in luxated teeth, as the pattern of results over time can guide decisions around "at-risk" teeth so that loss of vitality can be recognized and can then trigger endodontic intervention [2, 3].

While LDF is regarded as a highly accurate method for diagnosing the state of pulpal health and indeed comes closest to serving as a "gold standard," it must be recognized that LDF readings are prone to interferences from environmental and technique-related factors, including superimposed signals arising from blood flow in the periodontal tissues rather than in the pulp, the posture of the patient and their heart rate. If the laser light reaches the periodontium, then the reflected signal will not be entirely of pulpal origin [4–7]. One technique to overcome this is to place the probe on dentin in the floor of a cavity in the tooth, rather than on the enamel surface, since this is closer to the dental pulp and improves the signal-to-noise ratio [8].

There has also been work to explore the applications of transmitted laser light, rather than reflected laser light as in LDF. It has been suggested that transmitted light would be useful for the assessment of tooth pulp vitality both because the blood flow signals do not include flow of nonpulpal (e.g. periodontal) origin and because the response to blood flow changes are more obvious [9].

With both LDF and the transmitted light approach, it must be borne in mind that transmission of laser light may be influenced to some extend by tooth shade as well as by the presence of dental caries and restorations. Light can however be conducted within irregular secondary dentin, so the presence of carious lesions or tooth colored restorations in molar teeth does not always prevent laser light reaching the pulp space. Light will not, however, pass through amalgam restorations or gold crowns [10, 11].

Key Points for Laser Doppler Flowmetry

- Laser wavelengths must penetrate normal tooth structure.
- Visible red and near-infrared wavelengths are the most suitable.
- Finding a reproducible position for the tip is important of repeated measurements will be made.
- LDF cannot be used when the tooth is covered with an opaque full coverage restoration.

9.2.2 Fluorescence Diagnosis of the Root Canal System

Traditional culture-based techniques for assessing the presence of microorganisms in planktonic form or in biofilms in root canal system are difficult to use and prone to error. Real-time assessment of the microbial status of the root canal system using laser fluorescence has been developed to overcome these limitations and provide information that can guide clinical decisions around treatment endpoints [12].

The proof-of-concept for this application used an existing laser fluorescence device, the DIAGNOdent (KaVo, Biberach, Germany), which utilizes visible red laser light (wavelength 655 nm) to elicit fluorescence emissions in the near-infrared range. Initially this was used with a rigid sapphire tip to analyze the pulp chamber and coronal third of the root canal system in extracted teeth with infected and uninfected root canals. The fluorescence properties of bacterial cultures, mono-species biofilms in root canals, pulpal soft tissues, and sound dentin were also evaluated, together with extracted teeth with known endodontic pathology. The baseline for sound dentin and healthy pulpal soft tissue was established as an average fluorescence reading of 5 (on a scale of 100), whereas biofilms of *Enterococcus faecalis* and *Streptococcus mutans* established in root canals showed a progressive increase in fluorescence over time [13]. Fluorescence readings reduced to the "healthy" threshold reading of 5 when root canals were endodontically treated and the experimentally created bacterial biofilms were removed completely. High fluorescence readings were recorded in the root canals and pulp chambers of extracted teeth with radiographic evidence of periapical pathology and scanning electron microscopy evidence of bacterial infection. This confirmed that a laser fluorescence diagnostic approach could be useful for assessing the status of the pulp chamber and root canal system [13].

Development of thin flexible fiber tips to gain greater penetration into middle and apical thirds of the root canal was necessary to evaluate the performance of optical fibers (Fig. 9.1a, b). Fibers with either plain or conically modified

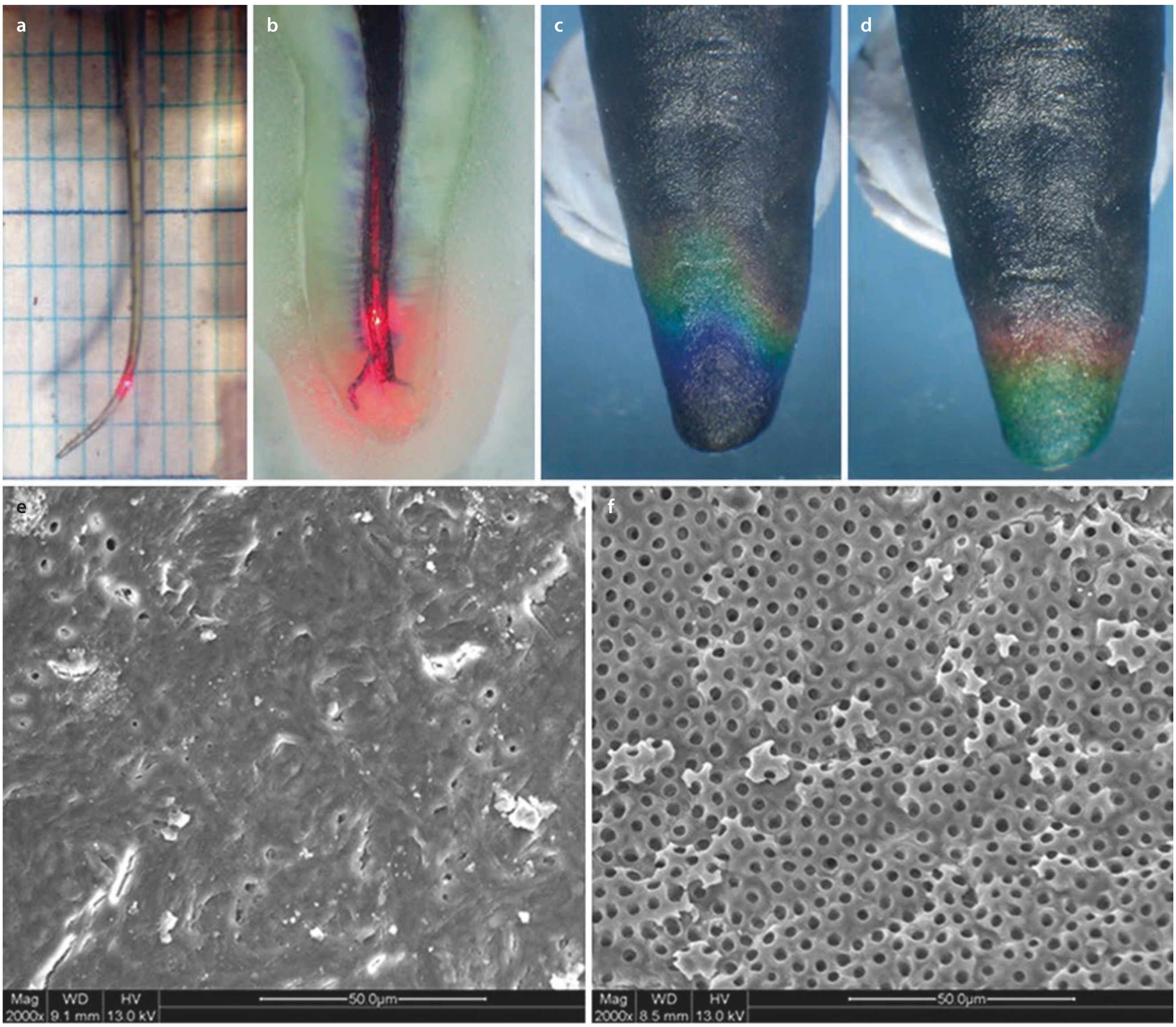


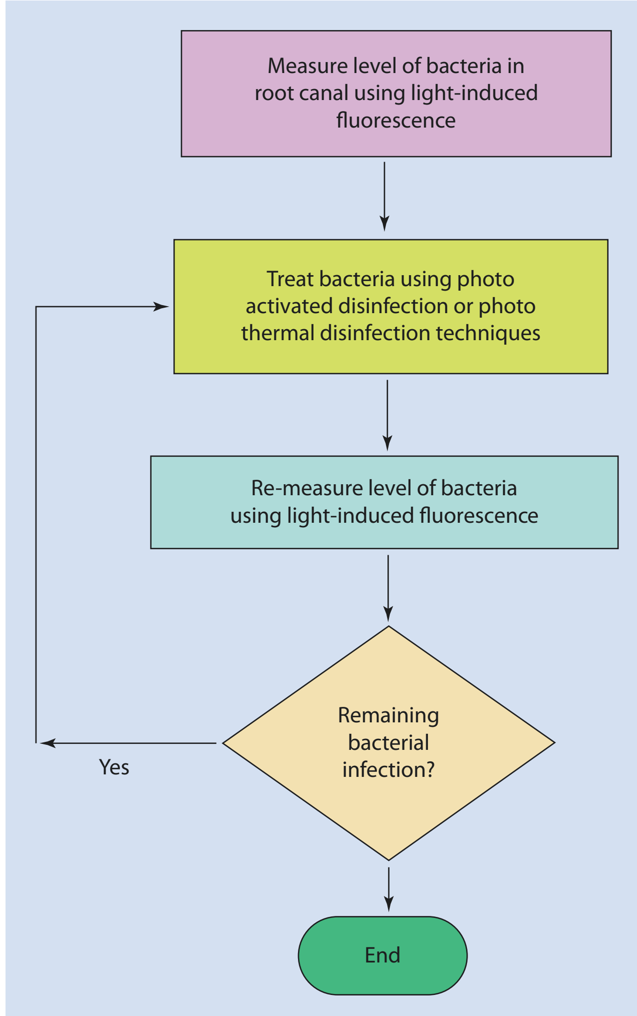
Fig. 9.1 Optical fibers and their applications in laser endodontics. **a** Conventional plain-ended fiber placed into an epoxy resin replica of the root canal showing forward emission of visible red laser energy. Using plain-ended tips requires the fiber to be moved to achieve irradiation of the canal walls. **b** Honeycomb fiber placed into the root canal showing lateral emission of visible red laser energy. To enhance visibility, the canal was filled with ink prior to inserting the fiber. **c** Thermochromic (heat sensitive) dye applied to the root surface showing subtle thermal changes during lasing of less than half a degree Celsius when the honeycomb tip is used to activate water-based fluid (500 mJ/pulse at 4 Hz). The point of greatest thermal change is the *blue color* change, followed by *green*, followed by *red*. **d** The same tooth 5 s after lasing has stopped, showing dissipation of thermal changes at the root surface. For details, see Ref. [14]. **e** Smear later present on the root canal walls when rotary instruments are used with water as the lubricant fluid. SEM magnification 2000×. **f** The same location after using a conical tip fiber to deliver 940 nm diode laser energy to activate EDTA irrigant. The laser was applied for 10 cycles of 10 s duration using 80 mJ/pulse at 50 Hz. For details, see Lagemann et al. [15]

ends, connected to a fluorescence diagnostic system, were also used to assess canals of extracted teeth with known periapical pathology. Diameter of fibers and their penetration into root canals with different curvatures were also tested. It was found that the fibers could reach the apical third of the root canal, unless the canals had distal curvatures greater than 15°. Penetration was greater for fiber optics with a conical/radial end design than for fibers with a plain/bare end design. The self-guiding action of the conical tip prevented frictional binding onto the canal walls and hence allowed for greater penetration. Fluorescence readings were significantly higher in infected canals (range, 19–99) than in noninfected canals and sound radicular dentin (range, 2–8) [16].

To further enhance the ability to take fluorescence fiber optic readings from the walls of the root canals, a cone-shaped tip with optimal properties for the lateral emission and collection of light was developed [17–19]. Commercial optical fibers were altered by tube etching with hydrofluoric acid, modified tube etching (after removing the protective polyimide coating), alumina abrasive particle beams, and etching and particle beams used in combination. Laser emissions both forward and laterally were measured and visibly traced using He-Ne lasers (632.8 nm) or InGaAsP diode lasers (635 and 670 nm). It was found that a particular etching/abrasion/etching combination gave a unique honeycomb surface configuration with grating-like properties. This had unique micro-patterns which were not seen on fibers which had been either etched or abraded. The honeycomb tips showed ideal radial emission and collection of light for fluorescence assessment of the root canal. This tip design was then used on fibers made of various materials and of different sizes [17–19].

The possibility now exists to combine fluorescence diagnostics with an endodontic treatment system (◘ Fig. 9.2). This has already been done for the removal of infected carious dentin and subgingival deposits of plaque, based on the fluorescence properties of the porphyrin compounds (contained in bacteria) [20–25]. For example, using the DIAGNOdent system, 655 nm visible red laser light elicits porphyrin fluorescence emissions over 780 nm in wavelength, which can readily be measured to give a quantitative relative fluorescence score ranging from 0 to 100. Healthy circumpulpal dentin, the walls of a healthy uninfected root canal and healthy dental pulp tissue all give fluorescence readings in the order of the 5–6 range using this method [13, 16] (◘ Fig. 9.3). There is also the possibility of using long wavelength ultraviolet light (380–400 nm) or violet light (405 nm) to elicit fluorescence emissions from bacterial deposits. In this instance, the emissions are in the visible red region [26–28].

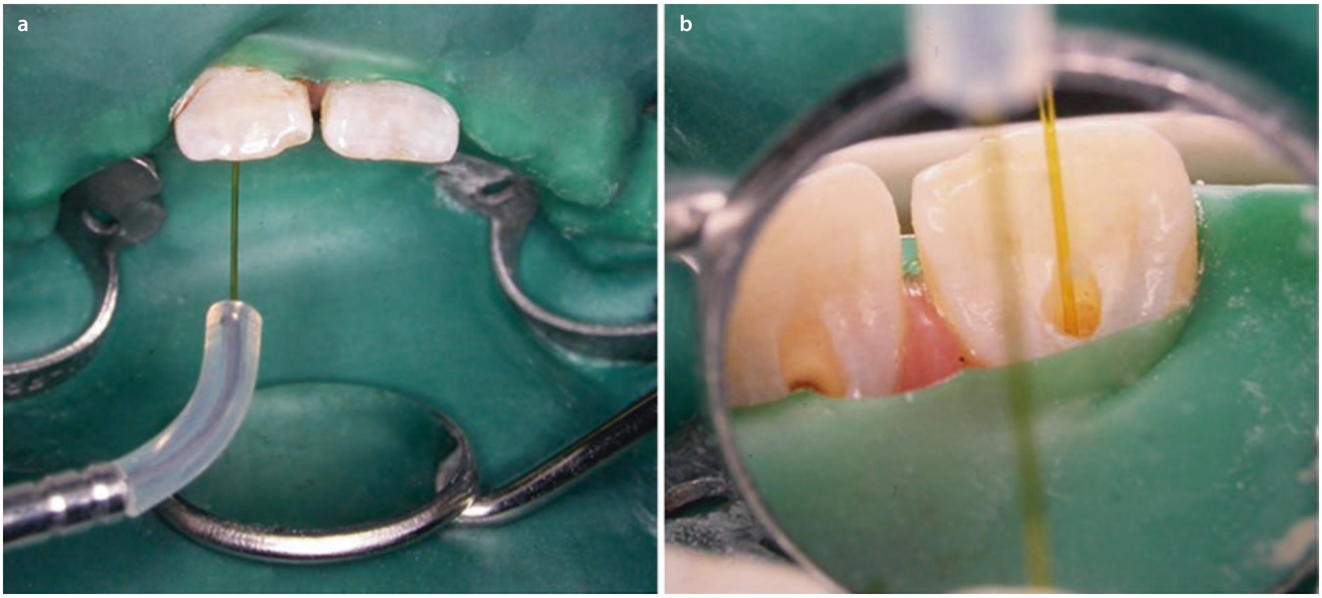
For the successful use of fluorescence to guide laser-based treatment methods, it is important to recognize factors which could impair the fluorescence process, for example, by quenching fluorescence emissions (such as hydrogen peroxide or ozone). After such treatments, fluorescence scores are suppressed and take up to 24 h to recover fully in the absence of exogenous antioxidants, meaning that there is a false negative (suggesting bacteria are absent when in fact they are still present). Use of suitable scavengers such as sodium ascorbate in solution can obviate such problems. It is also important to recognize situations, which give rise to false-positive signals (i.e. when bacteria are not present), such as when tetracyclines are used in medicament pastes, and rapidly become incorporated into the dentin of the root canal walls. The use of oxidant fluids (such as hydrogen peroxide or ozonated water) can quench fluorescence signals, unlike other fluids such as ethylene diamine tetraacetic acid (EDTA).



◘ **Fig. 9.2** Algorithm for using fluorescence to control laser-based debridement and disinfection (Adapted from Ref. [17] and US patent 8,977,085)

Key Points for Laser Fluorescence Assessment

- False-positive fluorescence can occur with certain endodontic medicaments (e.g. tetracyclines).
- Oxidants can quench fluorescence signals.
- Fiber optics with lateral light collection properties are required.
- Low laser powers are used so there are no deleterious thermal effects.
- Suitable wavelengths include ultraviolet, visible and near-infrared laser light.



9

Fig. 9.3 Use of real-time fiber optic detection of bacteria. A flexible fiber with a specially treated surface is inserted into the canal. The typical fiber diameter is 150–200 microns. The fiber is then linked to a fluorescence diagnostic system

9.2.3 Laser-Assisted Widening of the Root Canal

One of the earliest explorations of the possible use of lasers to enlarge the root canal was the study of Levy [29], in which an Nd:YAG laser with water spray was used to widen root canals in the apical zone from ISO #20 to ISO #35, based on the fit of K files. The technique employed was a painting and sweeping action circumferentially, with lateral pressure on the canal walls during withdrawal of the fiber. The procedure took 60 s, using of 300 mJ and 1 Hz. Consistent with this, Matsuoka et al. [30] required approximately 2 min to enlarge root canals from 0.285 to 0.470 mm. Both Ali et al. [31] and Jahan et al. [32] took only 60 s of lasing time to prepare the root canal using a crown-down technique. This excludes the time required to change fiber optic tips. It would be predicted that canals with larger tapers would be easier to prepare than those with narrower tapers.

With regard to the Ho:YAG laser, Cohen et al. [33] used a 245 μm diameter optical fiber to enlarge canals. The fiber was inserted to the apex, energized and then withdrawn slowly at 4 mm/s. Using this technique, canals with internal dimensions of ISO #25 were widened to an apical size of ISO #40. Using the same laser, Cohen et al. [34] employed a step back technique with four different optical fiber tips (with diameters of 140, 245, 355 and 410 μm) to enlarge canals progressively, whilst Deutsch et al. [35] used six different-sized optical fiber tips for enlarging the root canal with the Ho:YAG laser.

With regard to the Er,Cr:YSGG laser, Ali et al. [31] reported the use of fibers of various diameters to prepare root canals using a crown down technique. While noting that this laser wavelength was useful for removal of smear layer and debris, the risk of ledging, zipping, perforation or over-instrumentation of canals was noted. Matsuoka et al. [36] reported that the Er,Cr:YSGG laser could be used successfully to prepare root canals with curvatures up to 10 °, using a step back technique, with an average energy of 2 watts, a pulse rate of 20 Hz and air and water spray. In contrast, Jahan et al. [32] reported that preparation of canals with a curvature above 5° could lead to zipping, ledge formation or perforations. There is more limited information regarding use of the Er:YAG laser for enlarging the canal. Matsuoka et al. [30] reported using the Er:YAG lasers to enlarge the root canal using three different size conventional optical fiber tips used sequentially, in line with the step back approach.

Although several studies have shown the potential for lasers to widen the root canal, it is difficult to attain all of the mechanical objectives of root canal preparation when laser energy is delivered with conventional optical fibers. This relates to their inability to deliver laser energy directly onto the walls of the root canal, as well as the operator challenge of maintaining a constant withdrawal rate. In 2006, Altundasar et al. [37] showed that delivery of laser energy onto the walls of the root canal using a conventional (plain) optical fiber to remove smear layer gives inconsistent ablation. From the standpoint of optics, a beam delivered from a plain fiber (and thus largely parallel to the walls of the root canal surface to be ablated) has low efficiency, and this has been demonstrated in the laboratory setting, by comparing the effects of parallel and perpendicular beams directed onto root canal dentin slices.

In an attempt to overcome some of these problems, fiber tips with sculpted polished ends and greater lateral emissions have been developed [35, 38–42]. Shoji et al. [38] employed a cone-shaped irradiation tip which could disperse laser energy in an annular pattern. This aluminum reinforced silicate tip was used to deliver Er:YAG laser energy, to enlarge root canals. This tip design produced maximal enlargement when the laser was used at 30 mJ and 10 Hz.

Key Points for Laser-Assisted Widening of the Root Canal

- Laser wavelengths should ablate hard tissue for maximum effectiveness.
- Thermal side effects need to be controlled.
- Special tip designs improve safety and effectiveness.
- Suitable wavelengths are in the middle infrared.
- Laser energy must be pulsed to ensure thermal stresses are reduced.
- Concurrent irrigation assists cooling.

9.2.4 Removal of Smear Layer from Root Canal Walls

Many laser types have been reported to be useful in the removal of smear layer from root canal walls, including the argon fluoride (ArF) and other excimer lasers [43], argon ion lasers [44], KTP laser (532 nm) [45], diode lasers, Nd:YAG lasers [46, 47], HoYAG lasers [48], Er:YAG lasers [49, 50], Er,Cr:YSGG lasers [32, 51], and CO_2 lasers [52].

Diode lasers are cost-effective, compact and portable devices. The near-infrared laser emissions from these devices (810–980 nm) have penetrating disinfecting actions, which is an additional advantage to being able to remove smear layer. Wang [53] used a 980 nm wavelength diode laser at 5 W for 7 s to remove smear layer; however, concerns remain in terms of generation and conduction of heat to the supporting apparatus if high irradiances are used [54].

Nd:YAG lasers are more effective for disinfecting the root canal, and relatively less effective for removing smear layer, compared to the erbium lasers [55]. Goya [56], who investigated the effect of the Nd:YAG laser on smear layer, found that black ink increases the removal of smear layer by enhancing absorption of laser energy. However, Wilder-Smith et al. [57] identified that thermal damage was a concern when using the Nd:YAG laser to remove smear layer.

The water-absorbing properties of the Er:YAG and Er,Cr:YSGG lasers make these useful both for disinfection of the root canal and removal of smear layer [47, 51, 58]. Takeda et al. [47] undertook a comparative study of the argon ion laser (1 W, 50 mJ, 5 Hz), Nd:YAG laser (2 W, 200 mJ, 20 Hz.) and Er:YAG laser (1 W, 100 mJ, 10 Hz) in terms of removal of smear layer from prepared root canal walls, compared to EDTA. All lasers achieved better smear layer removal than EDTA, and the Er:YAG laser was the most effective of the three lasers used. In a later study, Takeda et al. [52] reported that Er:YAG lasers were better than CO_2 lasers and three different acids in removal of smear layer. Ali et al. [31] reported less smear layer or debris when using an Er,Cr:YSGG laser, compared to the conventional root canal techniques; however, the mechanical quality of the canal preparation (smoothness, taper, etc.) was worse with the laser method. Biedma [59] also reported similar results of that of Ali et al. [31], but using the Er:YAG laser.

As already noted, several studies have reported inconsistent or inefficient removal of smear layer when using erbium lasers delivered using conventional optical fibers. Altundasar et al. [60] reported inconsistent smear layer removal of the walls of the root canal when the Er,Cr:YSGG laser (operated at 3 W and 20 Hz) was delivered using a conventional tip, whilst Anic et al. [37] reported greater efficiency of a perpendicular beam for ablation when compared to a parallel beam. Kimura et al. [61] stated that it was difficult to evenly irradiate root canal walls using a conventional fiber tip and advocated an improvement in the fiber tip design or method of irradiation to avoid obtaining an uneven surface.

To overcome such problems, several authors have employed sculptured fiber tips that have greater lateral delivery of laser energy [38–40]. Alves et al. [41] used the Er:YAG with forward-emitting sapphire tips and hollow fibers and compared these to modified tips which gave lateral emissions. Shoji et al. [38] used an Er:YAG laser delivered into a cone-shaped tip to enlarge artificial root canals in a block of bovine dentin using Er:YAG laser energy. The cone-shaped tip was faster for cavity preparation and smear layer removal, compared with conventional instruments. Likewise, Takeda et al. [52] used a conical tip with the CO_2 to remove smear layer from the root canal.

Stabholz et al. [14] designed an endodontic side-firing spiral tip (RCLase; Lumenis, Opus Dent, Israel) (Fig. 9.3), which comprised a hollow waveguide with spiral slits along the length of the tube. The end of the tip was sealed to prevent the forward transmission of laser energy. The Er:YAG laser was used at 500 mJ and 12 Hz through this tip to remove smear layer successfully. However, such tips are too large and rigid to be used in narrow, curved root canals. Moreover, if the tip were to bend, more energy would be emitted across those slits that are in a straight line with the beam.

Key Points for Removal of Smear Layer

- Laser wavelengths should absorb strongly in water to generate cavitation.
- Use of pulsed modes is essential.
- Laser [pulse energy must be limited to prevent fluid extrusion from the apex and excessive projection of fluid from the root canal system.
- Most suitable laser wavelengths are in the middle infrared.
- Water-based irrigant fluids should be used; the procedure should never be done dry.
- Laser activation enhances the action of EDTA in smear layer removal.

- Lasers can enhance the actions of other water-based fluids such as sodium hypochlorite through agitation and warming of the fluid.
- Thermal side effects need to be controlled.
- Special tip designs improve safety and effectiveness.
- Tips degrade readily during use and this alters their emission characteristics.
- Laser energy must be pulsed to ensure thermal stresses are reduced.
- Concurrent irrigation assists cooling.

9.3 Disinfection

9.3.1 Photothermal Disinfection

Laser light can penetrate areas of canals where irrigating and disinfecting solutions cannot reach, such as fins, deltas, and lateral canals [62]. Selective photothermolysis occurs when laser energy is applied into the root canal system. For water-absorbing laser wavelengths, rapid expansion of water contained within microorganisms leads to their rupture, while for the visible and near-infrared wavelengths, primary absorption of laser energy into porphyrins, melanin, and other pigments occurs. The increase in temperature then denatures proteins and this renders the organisms unviable [63–65].

When such methods are used, it is important to employ pulsed modes and rest periods to allow for cooling of the root structure so that there is no collateral injury to the periodontal ligament from thermal stress. Assessments of safety undertaken in laboratory conditions are based on threshold values around 5.5–7 °Celsius as the limit of acceptable temperature increases on the root surface [66, 67].

Directing laser energy onto the walls of the root canal is essential for effective disinfection. To maximize this effect, different fiber modifications have been developed to increase lateral emission of laser energy, including designs with safe tips to reduce irradiation directed toward the root apex. Examples include conical tips, side-firing honeycomb tips, and honeycomb tips with silver-coated ends (safe ended fibers) [68].

Photothermal laser disinfection is a useful supplement to existing protocols for canal disinfection as the properties of laser light may allow a bactericidal effect beyond 1 mm of dentin. It must be remembered that endodontic pathogens can be present not only in the canal but extending into the dentin tubules for several hundred microns. This emphasizes the value of actions such as laser fluid agitation to enhance the efficacy of current irrigating protocols, which can increase the distance of the laser effect [69].

At the present time, the lasers used most commonly for photothermal disinfection are the Nd:YAG, KTP and near-infrared diode lasers. All of these have been shown to have excellent antibacterial efficacy, with greater penetration of the disinfecting action than middle-infrared wavelengths [70].

Key Points for Photothermal Disinfection

- Laser energy must absorb into major chromophores (water, porphyrins, melanin and other pigments) for bacterial inactivation to occur.
- Can be done with almost any laser system, but preferred lasers are Nd:YAG, KTP, and near-infrared diode lasers. Middle-infrared lasers will show the lowest penetration (~0.5 mm).
- Lateral-emitting/side-firing tips are preferred to ensure even irradiation is achieved.
- Disinfection can be achieved for microbial deposits deep within dentin which would not be reached by most medicaments placed into the canal.
- Penetration depths vary according to the laser wavelength used. Maximum penetration occurs with near-infrared laser energy.
- Pulsed modes must be used to lower thermal stress to the root and periodontium.
- Total dosimetry must be monitored so that the irradiation remains within safe limits.
- Movement of the fiber enhances coverage of the walls of the root canal.
- The fiber is moved from the apex in a coronal direction, tilting and rotating the fiber to help gain better exposure of the canal walls.
- The fiber must be kept in constant motion.
- Several passes one after the other are required to ensure that all parts of the root canal receive sufficient laser energy to inactivate microorganisms.

9.3.2 Photodynamic Disinfection

Photoactivated disinfection (PAD), also known as photoactivated chemotherapy (PACT), is based on the interaction of laser light with photosensitizers. These may be endogenous (such as porphyrins found in Gram-negative bacteria) or exogenous, in the form of dyes such as tolonium chloride or methylene blue applied into the root canal, which then bind to microbial outer membranes (Fig. 9.4). When the photosensitizer is exposed to laser light of the appropriate wavelength, reactive oxygen species are generated, which then damage the microbial cell membrane, leading to leakage of contents through it and denaturation of microbial proteins and DNA [65, 71].

Since LLP relies on the chromophore becoming electronically activated, it is essential to match the laser wavelength used with the chromophore, in exactly the same manner as is done for laser photodynamic therapy of oral lesions, where the laser energy activates otherwise nontoxic dyes producing reactive oxygen species that cause injury and death of tumour cells [72, 73].

PAD is a specific interaction, in that treatment with the laser alone (i.e. in the absence of the enhancing dye), or with the dye alone, produces much less microbial killing than the

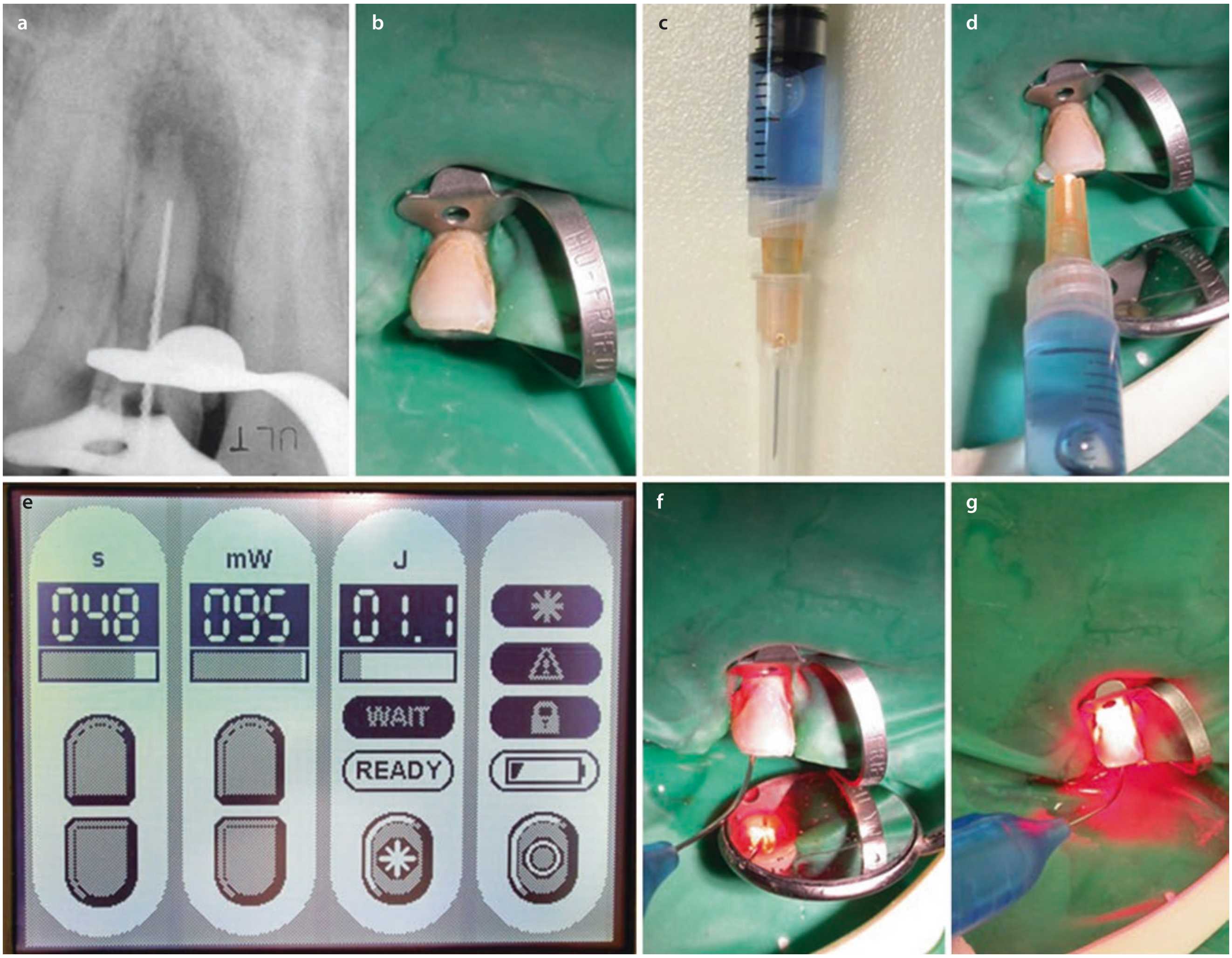


Fig. 9.4 Root canal photodynamic disinfection. This case presented with a large periapical lesion on the lateral incisor and apical root resorption. **a** Diagnostic file. **b** Isolated tooth. **c** Tolonium chloride dye solution. **d** Injection of dye solution into the root canal system. **e** Laser control panel for 635 nm diode laser midway during treatment showing delivered power 95 mW continuous wave mode. Typical irradiation is 60–90 s. **f, g** Transmission of visible red laser light through the coronal and radicular tooth structure. This activates the dye and provides biostimulation effects

combination of dye with laser. For example, using visible red laser light, bactericidal effects can be achieved using a range of blue, purple, and green dyes within the phenylmethane family, all of which are strong absorbers of red light [74, 75]. Other photosensitizers of interest include indocyanine green (ICG) and curcumin, which are activated at 808 and 470 nm, respectively [76, 77]. PAD can be undertaken with LEDs as well as with lasers, since either will activate the photosensitizers [78].

Both in vitro and clinical studies of PAD have demonstrated its ability to kill photosensitised oral bacteria (such as *Enterococcus faecalis*). To date, 12 studies have reported PAD as being effective in eliminating *Enterococcus faecalis* from infected root canals [79].

While PAD can be undertaken as part of the routine disinfection of the root canal system, it also has potential use for eradicating persistent endodontic infections for which conventional methods have been unsuccessful [80–82]. It does not cause significant thermal stress to the roots of teeth or the adjacent periodontal tissues [83].

There are many possible dyes which could be used for PAD. In its simplest form, the dye should undergo photodynamic activation and produce reactive oxygen species (ROS), which are the means by which microorganisms are inactivated. Dyes such as tolonium chloride and methylene blue are excellent producers of ROS in that regard. Using colored dyes which are activated by shorter wavelengths of light enhances effectiveness, since shorter wavelength light has a higher photon energy than longer wavelength light (such as in the near-infrared region of the spectrum).

There has been some confusion as to the mechanisms involved when green dyes such as indocyanine green (ICG) are exposed to near-infrared laser energy around 800–830 nm, which absorbs strongly in this material. The effect of the laser energy being absorbed is to heat the dye and therefore indirectly heat what the dye has become attached to. This is a type of photothermal disinfection process and is not a photodynamic process since the action is mediated through heat rather than through the generation of ROS. This underpins the applications of ICG dye in laser-based tumour therapies. ICG dye can absorb between 600 nm in the visible red region and all the way through to 900 nm, and it can emit fluorescence between 750 and 950 nm. ICG when exposed to 810 nm laser light will fluoresce, which is a major way ICG is used in medical diagnostics. Nevertheless, it is a simple fluorescence dye and is not a photosensitizer.

There has also been a level of confusion used in the terminology surrounding photodynamic disinfection, with terms such as photoactivated chemotherapy (PACT), photodisinfection and lethal laser photosensitization (LLP), all having been used to describe the effect with blue dyes; however, some studies using ICG also use these terms, which is incorrect.

Key Points for Photoactivated Disinfection

- Laser energy must absorb into the photosensitizer for bacterial inactivation to occur.
- Can be done with almost any visible or near-infrared laser system, as long as the laser wavelength matches the absorption of the dye.
- Preferred lasers are visible red (633, 635, 660, 670 nm) when blue dyes are used (tolonium chloride and methylene blue).
- Dyes used in photoactivated disinfection can also be activated using either lasers or LEDs.
- The liquid must be placed before laser activation to ensure adequate penetration into tubules and binding to bacteria.
- Effective dye solutions will contain low levels of surfactants to enhance penetration and reduce the formation of vapor locks.
- The dye used should not permanently stain teeth.
- Some dyes will effectively kill bacteria in the dark before being activated with laser light.
- Thermal effects caused by photoactivated disinfection are minimal.
- There are no adverse chemical effects on normal human cells.
- Lateral-emitting/side-firing tips are preferred to ensure even irradiation is achieved.
- Disinfection can be achieved for microbial deposits very deep within dentin which would not be reached by most medicaments placed into the canal.
- Penetration depths vary according to the dyes and laser wavelengths used.
- Longer irradiation times or multiple passes help ensure that all parts of the root canal receive sufficient laser energy to activate the dye to kill microorganisms.

9.4 Debridement of the Root Canal System

The use of lasers for debridement of the root canal systems offers several important advantages. Conventional instrumentation only touches some of the walls of the canal, since few canals are not perfectly round. Laser energy and laser-activated fluids, in contrast, can reach all the walls of the canal. In addition, use of files results in both widening and alterations in canal curvature. This problem of transportation does not occur when lasers are employed since energy can be delivered into the root canal without significant ablation of the walls of the root canal [84].

Finally, conventional instruments produce a smear layer, which then requires additional work to remove, such as alternating rinses with sodium hypochlorite and then extended periods of flushing with ethylene diamine tetraacetic acid (EDTA). Lasers can remove smear layer created by rotary or hand files and do not generate a smear layer when they are used to cut into root dentin.

9.4.1 Fluid Agitation

Sodium hypochlorite is the main irrigating solution used in endodontics to dissolve organic matter and kill microbes effectively. High concentration sodium hypochlorite (4%) has a better effect than 1 and 2% solutions. EDTA is needed as a final rinse to remove the smear layer [85]. Fluid agitation can enhance the action of irrigants such as sodium hypochlorite and EDTA. This agitation can be done using sonic activation or ultrasonic instruments. Greater cleanliness is achieved when endodontic irrigants are activated during the final irrigation regimen [86].

Because of their strong water absorption, Er:YAG and Er,Cr:YSGG lasers are ideally suited for activating fluids, both through warming them to enhance their chemical actions, and physically agitating them through cavitation actions (◘ Fig. 9.5). When using such lasers with water-based fluids in the canal, useful improvements can be gained in the removal of debris and smear layer (◘ Fig. 9.1f).

Using conical tips created using a tube-etching process, both Er:YAG and Er,Cr:YSGG lasers have been shown to be able to remove extraordinarily thick smear layers that had been created intentionally to provide a challenge to the laser system. When the extent of smear layer was assessed from scanning electron microscopy images with an objective digital method, it was found that lasing improved the action of EDTA in removing smear layer. Conical fibers performed better than plain fibers [68, 87].

Since the description of laser fluid activation in 2008, studies have documented the benefits of laser fluid agitation (also known as laser-activated irrigation, LAI) for enhancing cleaning of the root canal system, using EDTA, peroxide and sodium hypochlorite as the irrigant solutions. These show enhanced antibacterial actions for sodium hypochlorite and improved biofilm removal.

One of the variants of this is known as photon-induced photoacoustic streaming (PIPS), which is typically used with

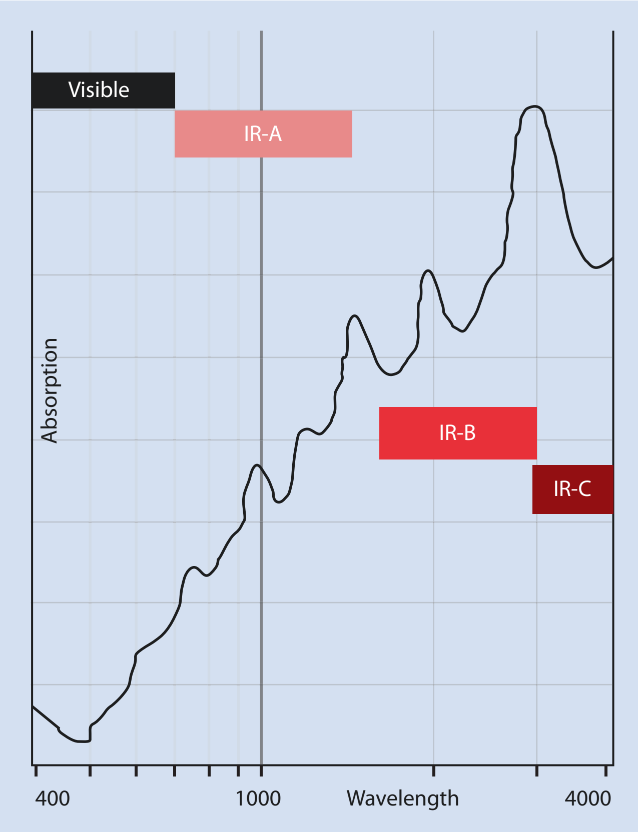


Fig. 9.5 Absorption of pure water in the visible region (400–700 nm) and adjacent infrared regions. The horizontal axis is wavelength in nanometers and the vertical axis is absorption. IR-A = 700–1400 nm; IR-B = 1400–3000 nm; IR-C = 3000 nm–1 mm

sodium hypochlorite. Laser-activated irrigation utilizing PIPS can enhance the disinfection of the root canal system [88–92].

Laser protocols which employ Er:YAG or Er,Cr:YSGG lasers with water-based fluids have been shown to cause minimal thermal stress to the root structure. Both plain and laterally emitting conical or honeycomb fiber tips can be used safely for intracanal irradiation without harmful thermal effects on the periodontium. When the irrigant fluid is refreshed between cycles of laser exposure, there is a strong beneficial effect on temperature, which attenuates completely the thermal effects of individual lasing cycles [93].

Key Points for Laser-Activation of Fluids

- Water-based fluids such as EDTA are preferred.
- Optimal lasers are the middle-infrared lasers which have strong water absorption.
- Absorption leads to cavitation and thus to agitation, fluid movement and shockwaves.
- Fluid can be ejected from the root canal, and the canal must then be topped up with kore fluid.
- Irrigation between lasing cycles reduces thermal stress.
- Excessively high pulse energies can cause fluid extrusion through the apical foramen.

9.4.2 Cavitation

With conventional irrigant solutions, fluid motion is limited to the relatively passive flow of fluid into and outside the root canal system. The root canal has confined geometry, which through surface tension effects makes the dispersion of irrigant more difficult because of the absence of turbulence over much of the canal volume [94]. Finally, in roots canals, the problems of bubble entrapment/vapor lock occur when using conventional irrigation approaches [95].

When lasers generate cavitation, the turbulence created agitates the fluids within the root canal. This can be done with the laser fiber stationary or being gently withdrawn. The laser tip does not have to be placed into the apical third of the root canal, while with conventional irrigation, it is important to place the tip of the irrigation needle to within 1 mm of the working length to ensure adequate fluid exchange [95, 96]. The laser-generated agitation causes fluid motion, which overcomes the bubble entrapment effect. Fluid streaming which is caused by the collapse of the laser-induced bubbles is a major aspect of how laser-activated fluids clean the walls of the root canal [97, 98].

Cavitation and agitation generated by lasers in fluid-filled root canals create fluid movement and shear stresses along the root canals walls, enhancing removal of the smear layer and biofilm. Rapid fluid motion is caused by expansion and subsequent implosion of laser-induced bubbles [99, 100].

When used with sodium hypochlorite and EDTA, laser activation of aqueous fluids can increase the efficiency of debridement and disinfection of root canals [101–103]. Moreover, there is now direct evidence that the pressure changes and shockwaves which accompany cavitation may enhance the susceptibility of bacteria in biofilms to antimicrobial agents. The problem of biofilms in root canals has direct parallels to the tubing of medical catheters, where such shock wave approaches are now attracting interest [104, 105].

An obvious problem which arises is whether fluid movement in the root canal leads to greater extrusion of fluids beyond the root apex. Conventional needles used for irrigation create apical pressure and extrude some fluid [106]. Studies of fluid extrusion beyond the apical constriction using Er:YAG and Er,Cr:YSGG lasers with bare or conical fiber tips positioned at distances of 5 or 10 mm from the apex have shown that the extent of microdroplets of fluid displaced past the apex was no greater than that seen when conventional 25-gauge non-side-venting irrigation needles were used [107].

When fibers with laterally emitting honeycomb patterns are used, these generate agitation with fluid movement directed onto the walls of the canal, while both the conventional plain fibers and tips with conical ends generate fluid movement largely in a forward direction. Having the laser energy directed laterally lowers the risk of fluid extrusion beyond the apex [103, 108].

Diode lasers in the 940–980 nm wavelength range can be used to generate cavitation, relying on their water absorption. Such lasers are used in pulsed modes, both to optimize the cavitation dynamics and to reduce collateral thermal effects on the roots (■ Fig. 9.1c, d). Such lasers can then be used with water-based fluids to remove debris and smear layers from the walls of the root canal. For diode lasers, the cavitation effects can be enhanced by supplementing the water with hydrogen peroxide to a final concentration of 3%. Any thermal stresses at the cementum are reduced when irrigation fluids are replaced, which enhances cooling of the root structure [109, 110].

In a recent study which evaluated the efficiency of EDTAC activation for smear layer removal using a 940 nm diode laser operated in pulsed mode and delivered by plain fiber tips into 15% EDTAC or 3% hydrogen peroxide, lasing EDTAC was found to considerably improve smear layer removal to a greater extent than lasing into peroxide. Of interest, the diode laser protocol for smear layer removal was more effective than the clinical "gold standard" protocol using EDTAC with sodium hypochlorite (NaOCl). In addition, when using diode lasers, there are additional benefits gained through photothermal disinfection and biostimulation [15].

When using a diode laser versus an erbium laser, it must be remembered that the fluid agitation effects are less for a diode laser than for an erbium laser; however, both are a great improvement on irrigants which are simply held static in the root canal [111].

Key Points for Laser-Induced Cavitation

- Laser energy must absorb into water for cavitation to occur in a water-based fluid.
- A small volume of water will show greater cavitation than a large volume for the same laser pulse energy; this has relevance to the effects seen in small versus large diameter canals.
- Middle-infrared lasers (Er:YAG and Er,Cr:YSGG) will show the fastest cavitation (microseconds) versus 940–980 nm diode lasers (seconds) and will cause the fastest fluid motion in the canal.
- Lateral-emitting/side-firing tips are preferred as this changes the direction of cavitation bubble formation and collapse.
- Pulsed modes must be used; shorter pulse durations will cause greater cavitation to occur for the same pulse energy, but will increase the risk of fluid extrusion through the apex.
- More fluid extrusion occurs when the apical foramen is larger.

9.5 Laser-Enhanced Bleaching

Sclerosis following dental trauma and the severe forms of intrinsic staining due to loss of vitality or endodontic treatment are challenging to manage. Some of these conditions are resistant to conventional bleaching treatments based on carbamide or hydrogen peroxide. Common factors in intrinsic staining include demeclocycline-containing tetracycline medicaments and bismuth oxide, an agent used to achieve radiopacity in some epoxy resin sealers and in mineral trioxide aggregate (MTA) [112–115].

The underlying chemistry which explains the patterns of discoloration with these different types of materials is quite complex. In the case of MTA, it is the formation of bismuth sulphide, which is black in color and therefore causes the tooth to appear grey. Iron released from hemoglobin following trauma can also form iron sulphide. Such sulphide compounds are very stable and not readily oxidized [116].

Removal of tetracycline medicaments from the root canal does not prevent later discoloration. In fact, studies have shown that current irrigation methods using plain needles, open-ended notched irrigation needles or side-vented needles do not completely remove all traces of such medicaments [117]. Laser-activated irrigation is however significantly more effective for removing endodontic medicaments than any protocols based on needle irrigation [118].

Tetracyclines bind readily to tooth structure and then form a red-purple degradation tetracycline product (4 alpha, 12 alpha-anhydro-4-oxo-4-dedimethylaminotetracycline, known as AODTC) when moisture is present. AODTC is resistant to oxidation, but can undergo photolysis when exposed to visible green light (530–535 nm), opening up possibilities for laser therapy using a KTP laser (■ Fig. 9.6) [119–121].

There are numerous ways that lasers can be used to enhance bleaching. These include photothermal effects (warming the gel to make hydrogen peroxide more active chemically), photochemical actions (such as the Fenton reaction), photocatalytic actions, and photodynamic actions, where the laser energy activates a suitable photosensitizer. There is also photo-oxidation, an effect which is essential for breaking up tetracyclines and AODTC [122].

Sclerosed discolored traumatized teeth, which have remained vital, can be treated using the KTP laser with photodynamic bleaching, employing rhodamine as the photosensitizer. The same technique can also be used successfully to treat using external bleaching applied in the office setting nonvital teeth with stains from endodontic treatment and teeth with tetracycline staining [123].

We undertook a clinical study of photodynamic bleaching for treating confirmed cases of tetracycline discoloration as a single-appointment procedure used the KTP (frequency doubled Nd:YAG) laser (wavelength 532 nm) combined with a rhodamine-B photosensitizer gel (Smartbleach) applied to the teeth and activated for 30 sec. Each tooth underwent four cycles of 30 s of laser exposure. Digital image analysis was undertaken in a blinded manner, and this showed a significant lightening effect was achieved in 78% of the teeth treated. An in-office KTP laser photodynamic bleaching treatment provides a useful option for improving tooth shade in teeth with tetracycline discoloration [124].

In later work, we showed that KTP laser photodynamic bleaching for tetracycline staining was more effective than using arrays of LEDs in the visible green range (535 nm) with the same photosensitizer or photo-Fenton bleaching using LED arrays in the visible blue (460 nm) [125, 126].

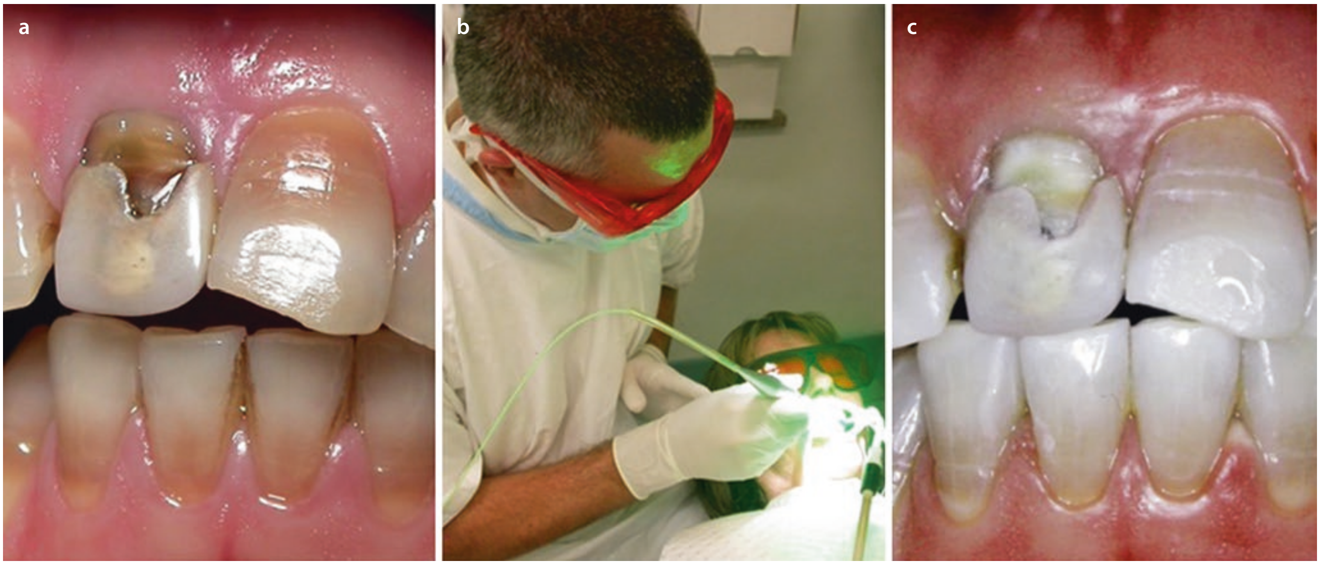


Fig. 9.6 KTP laser photodynamic bleaching of a discolored non-vital maxillary central incisor tooth (11) from an external approach. **a** Preoperative view of the discolored tooth. All the teeth have tetracycline staining of developmental origin. Tooth 11 has undergone endodontic treatment. **b** Application of KTP laser onto a rhodamine photosensitizer in repeated cycles, to treat all the anterior teeth. **c** Postoperative view at the end of the same appointment. There has been a useful improvement in the shade of the root-filled 11 tooth as well as the adjacent teeth from the laser treatment. A tooth colored restoration was subsequently placed 2 weeks later to restore the 11 tooth

Key Points for Laser-Assisted Bleaching

- Photo-thermal laser bleaching requires careful control of the irradiation protocol to limit heat stress to the dental pulp.
- Photodynamic laser bleaching is effective for more challenging intrinsic stains including tetracyclines deposited during tooth formation and sclerosed vital teeth.
- External bleaching approaches overcome problems of invasive cervical resorption associated with internal bleaching (walking bleach) methods where peroxides can come into contact with periodontal tissues.

9.6 Laser-Induced Analgesia and Photobiomodulation

Studies of restorative dentistry using free-running pulsed Nd:YAG lasers conducted in the early 1990s showed that pulsed laser radiation which could penetrate dentin was responsible for a component of the desensitizing effect of this laser on sensitive cervical dentin. Later studies of laser-induced analgesia with the free-running pulsed Nd:YAG and Er:YAG lasers by Orchardson and Zeredo, respectively, using rodents showed conclusively that there was a dramatic blockage of neuronal activity and a corresponding increase in the pain threshold of teeth after laser irradiation. The effect had a clear dose response for its onset, declined after 15–20 min, and was also associated with blockade of late-phase neurogenic inflammation (which is driven by the effects of neuropeptides). These effects were identical to those noted in clinical practice when preparing cavities with erbium lasers (Er:YAG and Er,Cr:YSGG). The animal studies however removed all possibility of placebo effects and psychogenic influences and demonstrated that there was a fundamental reversible alteration occurring in the nociceptive response caused by the laser treatment, which suppressed nerve firing for a given level of stimulus [127–131].

These effects can be used therapeutically for analgesia associated with restorative dentistry, oral surgery (including bone ablation procedures) and for endodontic procedures, including pulp capping and extirpation. Clinically, the blockade with shorter exposures is more selective for depolarization of A delta fibers (rapid, sharp, well-localized pain) than for C fibers, which explains why some patients experience vibrational sensations but not discomfort [132].

Analgesic effects can be induced by diode lasers operated in pulsed or continuous wave mode, as well as by pulsed Nd:YAG and middle-infrared erbium lasers. With the former, the wavelength and irradiance are key variables in determining the potency of the effect, while with the latter, the pulse energy and pulse frequency are critical variables [71, 133–136].

Low-level laser therapy (LLLT), also known as soft laser, biostimulation or photobiomodulation, is another laser effect of interest in endodontics. This photochemical effect arises from the action of visible red (633–635 nm) or near-infrared (810–1100 nm) light on the enzymes of the electron transport chain in mitochondria, resulting in a broad activation of normal cellular functions. LLLT effects underpin the beneficial effects of lasers when used for pulp capping and pulpotomy, where there is direct exposure of pulpal soft tissues. This explains why there is accelerated healing, nerve sprouting and dentinogenesis after pulpotomy [137].

Bystander LLLT effects occur in the periodontal ligament and periapical bone when lasers are used for intracanal procedures such as disinfection and promote the resolution of inflammation and healing responses after infection [65, 138].

Key Points for Laser-Induced Analgesia

- Analgesic effects can be induced with near- or middle-infrared lasers.
- Irradiation parameters for analgesia with diode lasers are higher than those for enhancement of wound healing and other photobiomodulation treatments with the same lasers.
- Laser-induced analgesia effects occur when lasers are used to treat hypersensitive cervical dentin and contribute to the overall clinical effects seen.

9.7 Pulp Therapy and Pulpotomy

Pulpotomy techniques for primary teeth traditionally have used formocresol, but this is becoming less widely used because of its toxic effects on living tissues and mutagenic potential. Alternatives such as MTA are expensive, and this has led to interest in using lasers for pulpotomy procedures. The lasers used have included Nd:YAG, Er:YAG, carbon dioxide and 632 or 980 nm diode lasers.

Several clinical studies support the use of lasers for pulpotomy. The reported advantages include better clinical as well as radiographic outcomes than ferric sulphate, MTA or electrosurgery, as well as a shorter operating time, simpler procedure and less postoperative pain. Effective photothermal disinfection combined with low-level laser effects likely accounts for the favorable outcomes seen clinically with laser pulpotomy [139–142]. Similarly, there is clinical trial data to support the effectiveness of direct pulp capping using lasers with carbon dioxide, 808 nm diode, Er:YAG and Er,Cr:YSGG lasers (Fig. 9.7) [143–147].

Key Points for Laser Pulpotomy

- Laser energy must absorb into major chromophores (water, porphyrins, melanin and other pigments) for coagulation and bacterial inactivation to occur
- Can be done with almost any laser system, but preferred lasers are Nd:YAG, KTP and near-infrared diode lasers.
- If middle-infrared lasers are used, long pulse durations are needed to maximize coagulation
- Typically employs very short exposure times
- The techniques to treat the exposed pulp stumps are the same as for direct pulp capping

9.8 Endodontic Surgery and Treatment of Resorption Lesions

Lesions of invasive cervical resorption can be treated by laser ablation, as an alternative to the traditional approach using trichloracetic acid. The advantages of using lasers for this application include greater precision and less collateral injury to the tissues (Fig. 9.8) [148].

For periapical surgery, lasers can be used to ablate granulation tissue and to sterilize the root apex, as well as for gaining access to the lesion by removing overlying bone. Bone is ablated readily by Er:YAG and Er,Cr:YSGG laser radiation, and in clinical practice, this is typically undertaken using an accompanying water mist spray. Appropriate flow of water spray prevents desiccation of bone, ensures cooling of the site to maintain bone viability, and irrigates the site to remove debris. These middle-infrared lasers give deep cuts with sharp edges which are free of charring. Similar benefits are found when these lasers are used for root resection procedures [149, 150].

Lasers have been used successfully for root-end resection and root-end cavity preparation during apical surgery [151]. Use of an Er:YAG or Er,Cr:YSGG laser with an operating microscope for periapical surgery has been shown to give significantly better results in terms of postoperative healing, in comparison with using conventional surgical approaches

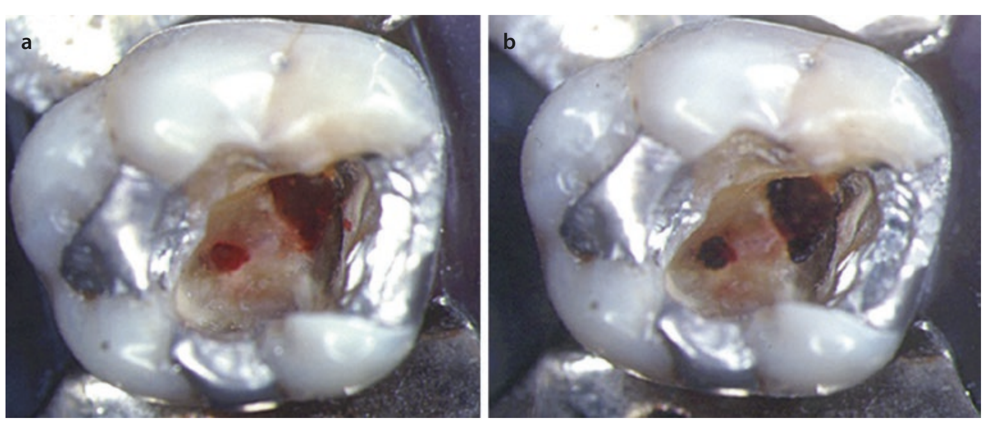


Fig. 9.7 Vital pulp capping. **a** Bleeding pulp at the base of the cavity preparation following an iatrogenic exposure of vital pulp tissue. **b** immediately after firing several pulses of carbon dioxide laser radiation to seal the area and control bleeding. The cavity was then lined with glass ionomer cement and the tooth restored with amalgam. There was no loss of vitality over time

Fig. 9.8 Laser treatment of invasive cervical resorption. Tooth 21 (left maxillary central incisor) distal developed invasive resorption after internal "walking" bleaching with hydrogen peroxide. The bleaching occurred prior to PFM crowns being placed on both maxillary central incisor teeth. **a** Preoperative view. **b** With a flap raised the granulation tissue filling the resorption defects on the root surface can be seen. **c** Pulses from a carbon dioxide laser were used to ablate the resorbing granulation tissue. After this the root surface was conditioned and a glass ionomer cement restoration placed. **d** 12 month follow-up showing a stable situation

for apicoectomy. Such lasers can be used safely for root resections provided short pulse duration is used and the water spray flow rate is sufficient [152, 153].

Key Points for Laser Endodontic Surgery

- Laser energy must absorb into major chromophores (water, porphyrins, melanin and other pigments) for soft tissue ablation to occur
- Can be done with almost any laser system, but preferred lasers are Nd:YAG, KTP and near-infrared diode lasers. With the carbon dioxide laser, extreme care is needed to avoid deleterious thermal changes to tooth structure and the dental pulp.
- Hard tissue ablation (bone cutting, root-end resection) requires a middle-infrared laser for high cutting efficiency.

9.9 Safety Issues Related to the Use of Lasers in Endodontics

Lasers can be used in conjunction with conventional endodontic equipment such as operating microscopes provided the appropriate considerations are made for eye safety, such as filters fitted to the objective of the microscope to match the laser wavelengths in use. With wavelengths longer than 2000 nm, this is not needed as the glass elements in the microscope provide sufficient attenuation.

9.9.1 Prevention of Transmission of Infection Through Contact

Laser endodontic fibers tips used within the root canal would be expected in many cases to encounter blood or other fluids which could be a source of patient-to-patient transmission of infection, if the fibers are not appropriately disinfected. Disposable tips have become available for some laser systems; however, many fiber optic systems are used where the fibers are cleaved after each use [154]. Appropriate disinfection and sterilization must be carried out for laser accessories and components that come into direct contact with oral soft and hard tissues. Other relevant recommendations include:

1. Fluid fed through a sleeve around the laser to cool it during surgery must be sterile.
2. Deposits of carbonized tissue residue can reduce the quantity and quality of the light emission. Therefore, it is necessary to wipe the tip after use. It may be necessary to calibrate the tip during the procedure.
3. Sapphire tips that come into contact with sterile tissue must be sterile and need to be cleaned and then sterilized after each use.

Piccione [155] further recommended that all controls of the laser should be disinfected or covered with a barrier, in a manner similar to other dental equipment, while smaller laser accessories such as handpiece should be steam sterilized.

9.9.2 Temperature Effects of Lasers on the Dental Pulp

In all endodontic applications using higher powered lasers, care is needed to address thermal changes in the root structure, to preserve tissue vitality. Andersen [156] has demonstrated that in the human dental pulp, both cold and heat evoked a decrease in pulpal blood flow, when measured using a Doppler flowmetry. There is, therefore, a low potential of pulpal blood flow for cooling. The absorption coefficient and the reflectivity of the laser wavelength used are important in determining the pulpal reaction. Nyborg and Brannstrom [157] determined that a temperature of 150 °C on the enamel surface for 30 s could cause necrosis of the dental pulp. According to Zach and Cohen [66], an intra-pulpal temperature increase of approximately 5.5 °C can promote necrosis of the dental pulp in 15% of cases, while temperature increases of 11 and 17 °C will cause necrosis in 60 and 100% of cases [66, 158].

Pulpal damage can be avoided or minimized by a suitable choice of laser parameters and by appropriate use of irrigation or an air/water spray. Armengo [159] studied the effect of water spray on the temperature rise when using an Er:YAG or Nd:YAP laser. Water spray reduced the temperature rise associated with laser treatment and also helped to clear the ablation site of debris and keep it moist. The importance of air/water spray is exemplified in the study of Glockner et al. [160], which demonstrated that during coronal cavity preparation with the Er:YAG laser, a temperature reduction occur after a few seconds from 37 to 25 °C, because of the cooling effect of the air/water spray.

9.9.3 Temperature Effect of Lasers on Periodontal Tissues

Maintaining the health of the periodontal apparatus is critical for the success or failure of endodontic treatment undertaken with lasers. Modern endodontic rotary instruments produce little or no increase in peri-radicular root surface temperature [161]. In contrast, several studies have shown that certain canal preparation techniques [162, 163] and obturation techniques [164–167] can transfer heat to the periodontal tissues. Er:YAG lasers cause evaporation and expansion of water within the crystals of hard tissue, and this evaporation can have a cooling action.

Several authors have studied the thermal effect of lasers on the periodontal ligament and surrounding bone [33, 34, 168, 169]. The supporting periodontal apparatus is known to be sensitive to temperatures of 47 °C, while temperatures of 60 °C and above will permanently stop blood flow and cause bone necrosis [170]. On the other hand, periodontal tissues are not damaged if the temperature increase is kept below 5° Celsius [171]. A threshold temperature increase of 7 °C is commonly considered as the highest thermal change which is biologically acceptable to avoid periodontal damage [67, 172–174].

Kimura et al. [175] using the Er:YAG laser noted that the root surface temperature increase was less than 6 °C at the apical third and 3 °C at the middle third. Similarly, Theodoro et al. [176] using the same laser reported temperature increases below 7 °C, while in the study of Machida et al. [172] where water spray was used, the temperature increase at the apex was less than 2 °C. Thus, the use of air or water coolants in combination with lasers will help prevent adverse thermal effects on the periodontal ligament and surrounding bone [159, 160].

A further consideration is that of the thermal relaxation time (T_R), which is the amount of time required for heat to flow into adjacent regions or otherwise be dissipated [177]. The use of pulsed lasers with short pulse durations will minimize the zone of thermal damage, by producing a thermal event that is shorter than the T_R of the tissue [178].

In case of root canal ablation, the conduction of heat from dentin to periodontal ligament and bone can be reduced by using a continuous stream of water during ablation. On the other hand, a dry root canal is devoid of fluid and will conduct energy similar to a solid body, which is uniformly in all directions. However, canals that are irrigated with fluids will benefit from transfer of heat into that fluid.

9.10 Future Aspects

The use of lasers in endodontics has entered a new phase with research over the past decade indicating that laser-based methods can provide not only equivalent but now superior results in terms of effective debridement of the root canal when compared to hand or powered conventional endodontic instruments. The potential in the future is to link systems for debridement and disinfection to approaches which also give accompanying analgesic effects and biostimulation, so that several therapeutic benefits are gained at the same time from a single laser irradiation protocol. There is considerable potential to incorporate feedback systems into endodontic laser systems so that fibers used within the root canal space for treatment can also support detection and diagnosis applications. This will enhance clinical efficiency and reduce the complexity of equipment which clinicians use. Further development of techniques for laser-induced analgesia will promote the development of endodontic and restorative treatments of teeth.

Conclusion

There are now several areas in endodontics where the use of laser technology offers superior outcomes for patients and simplification of techniques for the clinician. Pulsed near- or middle-infrared lasers combined with irrigants provide several advantages in terms of effective canal debridement as well as accompanying disinfection. Given the growing evidence in support of such applications, the integration of laser-based technologies into everyday clinical practice is likely to grow over the coming years. A wide range of lasers have been used successfully in endodontics, and this opens the pathway for laser systems which offer more than one wavelength, delivered through separate delivery systems or the one delivery system.

References

1. Abd-Elmeguid A, Yu DC. Dental pulp neurophysiology: part 2. Current diagnostic tests to assess pulp vitality. J Can Dent Assoc. 2009;75(2):139–43.
2. Emshoff R, Moschen I, Strobl H. Use of laser Doppler flowmetry to predict vitality of luxated or avulsed permanent teeth. Oral Surg Oral Med Oral Pathol Oral Radiol Endod. 2004;98(6):750–5.
3. Roy E, et al. Evaluation of the ability of laser Doppler flowmetry for the assessment of pulp vitality in general dental practice. Oral Surg Oral Med Oral Pathol Oral Radiol Endod. 2008;106(4):615–20.
4. Firestone AR, Wheatley AM, Thuer UW. Measurement of blood perfusion in the dental pulp with laser Doppler flowmetry. Int J Microcirc Clin Exp. 1997;17(6):298–304.
5. Jafarzadeh H. Laser Doppler flowmetry in endodontics: a review. Int Endod J. 2009;42(6):476–90.
6. Odor TM, et al. Laser light transmission in teeth: a study of the patterns in different species. Int Endod J. 1999;32(4):296–302.
7. Alghaithy RA, Qualtrough AJ. Pulp sensibility and vitality tests for diagnosing pulpal health in permanent teeth: a critical review. Int Endod J. 2017;50(2):135–42. doi: 10.1111/iej.12611. Epub 2016 Feb 11.
8. Banthitkhunanon P, et al. Effects of enamel and dentine thickness on laser Doppler blood-flow signals recorded from the underlying pulp cavity in human teeth in vitro. Arch Oral Biol. 2013;58(11):1692–5.
9. Sasano T, et al. Possible application of transmitted laser light for the assessment of human pulpal vitality. Endod Dent Traumatol. 1997;13(2):88–91.
10. Chandler NP, Pitt Ford TR, Watson TF. Pattern of transmission of laser light through carious molar teeth. Int Endod J. 2001;34(7):526–32.
11. Chandler NP, Pitt Ford TR, Monteith BD. Laser light passage through restored and carious posterior teeth. J Oral Rehabil. 2014;41(8):630–4.
12. Walsh LJ. Applications of laser fluorescence for diagnosis of bacterial infections in the root canal. Australas Dent Pract. 2010;21:54–6.
13. Sainsbury AL, Bird PS, Walsh LJ. DIAGNOdent laser fluorescence assessment of endodontic infection. J Endod. 2009;35(10):1404–7.
14. Stabholz A, et al. The use of lasers in dentistry: principles of operation and clinical applications. Compend Contin Educ Dent. 2003;24(12):935–48.
15. Lagemann M, et al. Activation of ethylenediaminetetraacetic acid by a 940 nm diode laser for enhanced removal of smear layer. Aust Endod J. 2014;40(2):72–5.
16. Ho QV, et al. Laser fluorescence assessment of the root canal using plain and conical optical fibers. J Endod. 2010;36(1):119–22.
17. George R, Walsh LJ. Performance assessment of novel side firing flexible optical fibers for dental applications. Lasers Surg Med. 2009;41(3):214–21.
18. Shakibaie F, George R, Walsh LJ. Applications of laser-induced fluorescence in dentistry. Int J Dent Clin. 2011;3(3):38–44.
19. George R, Walsh LJ. Laser fiber-optic modifications and their role in endodontics. J Laser Dent. 2012;20:24–30.
20. Krause F, et al. Laser fluorescence measurements compared to electrical resistance of residual dentine in excavated cavities in vivo. Caries Res. 2007;41(2):135–40.
21. Clark J, et al. Effectiveness of diagnosing residual caries with various methods during cavity preparation using conventional methods, chemo-mechanical caries removal, and Er:YAG laser. Aust Dent J. 2001;46:S20.
22. Yonemoto K, et al. Application of DIAGNOdent as a guide for removing carious dentin with Er:YAG laser. J Dent. 2006;34:269–76.
23. Eberhard J, et al. Evaluation of selective caries removal by a fluorescence feedback-controlled Er:YAG laser in vitro. Caries Res. 2005;39(6):496–504.
24. Folwaczny M, et al. Root substance removal with Er:YAG laser radiation at different parameters using a new delivery system. J Periodontol. 2000;71(2):147–55.
25. Krause F, et al. Evaluation of selective calculus removal by a fluorescence feedback-controlled Er:YAG laser in vitro. J Clin Periodontol. 2007;34(1):66–71.
26. Walsh LJ, Mubarak S, Mcquillan A. Autopilot laser-based systems for guiding caries and calculus removal: from concept to clinical reality. Australas Dent Pract. 2007;18:122–8.
27. Coulthwaite L, et al. The microbiological origin of fluorescence observed in plaque on dentures during QLF analysis. Caries Res. 2006;40(2):112–6.
28. Walsh LJ, Shakibaie F. Ultraviolet-induced fluorescence: shedding new light on dental biofilms and dental caries. Australas Dent Pract. 2007;18:52–6.
29. Levy G. Cleaning and shaping the root canal with a Nd:YAG laser beam: a comparative study. J Endod. 1992;18(3):123–7.
30. Matsuoka E, et al. Morphological study on the capability of Er:YAG laser irradiation for root canal preparation. J Clin Laser Med Surg. 2000;18(4):215–9.
31. Ali MN, et al. Efficacy of root canal preparation by Er,Cr:YSGG laser irradiation with crown-down technique in vitro. Photomed Laser Surg. 2005;23(2):196–201.
32. Jahan K, et al. An assessment following root canal preparation by Er,Cr:YSGG laser irradiation in straight and curved roots, in vitro. Lasers Med Sci. 2006;21(4):229–34.
33. Cohen BI, Deutsch AS, Musikant BL. Effect of power settings on temperature change at the root surface when using a Holmium YAG laser in enlarging the root canal. J Endod. 1996;22(11):596–9.
34. Cohen BI, et al. Effect of power settings versus temperature change at the root surface when using multiple fiber sizes with a Holmium YAG laser while enlarging a root canal. J Endod. 1998;24(12):802–6.

35. Deutsch AS, Cohen BI, Musikant BL. Temperature change at the root surface when enlarging a root canal with a holmium: YAG (Ho:YAG) laser, using six different fiber-optic sizes. Gen Dent. 2004;52(3):222–7.
36. Matsuoka E, Jayawardena JA, Matsumoto K. Morphological study of the Er,Cr:YSGG laser for root canal preparation in mandibular incisors with curved root canals. Photomed Laser Surg. 2005;23(5):480–4.
37. Anic I, et al. Scanning electron microscopic study of dentin lased with argon, CO2, and Nd:YAG laser. J Endod. 1998;24(2):77–81.
38. Shoji S, Hariu H, Horiuchi H. Canal enlargement by Er:YAG laser using a cone-shaped irradiation tip. J Endod. 2000;26(8):454–8.
39. Martin. Comparison of the emission characteristics of three erbium laser systems-a physical case report. J Oral Laser Appl. 2004;4(4):263–9.
40. Verdaasdonkz RM, van Swol CF. Laser light delivery systems for medical applications. Phys Med Biol. 1997;42:869–94.
41. Alves PR, et al. Evaluation of hollow fiberoptic tips for the conduction of Er:YAG laser. Photomed Laser Surg. 2005;23(4):410–5.
42. Shirk GJ, Gimpelson RJ, Krewer K. Comparison of tissue effects with sculptured fiberoptic cables and other Nd:YAG laser and argon laser treatments. Lasers Surg Med. 1991;11(6):563–8.
43. Stabholz A, et al. Effect of ArF-193 nm excimer laser on human dentinal tubules. A scanning electron microscopic study. Oral Surg Oral Med Oral Pathol. 1993;75(1):90–4.
44. Harashima T, et al. Effect of argon laser irradiation on instrumented root canal walls. Endod Dent Traumatol. 1998;14(1):26–30.
45. Tewfik HM, et al. Structural and functional changes in root dentin following exposure to KTP/532 laser. J Endod. 1993;19(10):492–7.
46. Harashima T, et al. Effect of Nd:YAG laser irradiation for removal of intracanal debris and smear layer in extracted human teeth. J Clin Laser Med Surg. 1997;15(3):131–5.
47. Takeda FH, et al. Comparative study about the removal of smear layer by three types of laser devices. J Clin Laser Med Surg. 1998;16(2):117–22.
48. Nuebler-Moritz M, Gutknecht N, Sailer HF, Hering P, Prettl W et al. Laboratory investigation of the efficacy of holmium: YAG laser irradiation in removing intracanal debris, in Lasers in Dentistry III. In: Wingdor Harvey A, Featherstone jdb, Rechman P editors. Proc SPIE; 1997;2973:150–6.
49. Kesler G, et al. Histological and scanning electron microscope examination of root canal after preparation with Er:YAG laser microprobe: a preliminary in vitro study. J Clin Laser Med Surg. 2002;20(5):269–77.
50. Takeda FH, et al. Efficacy of Er:YAG laser irradiation in removing debris and smear layer on root canal walls. J Endod. 1998;24(8):548–51.
51. Yamazaki R, et al. Effects of erbium,chromium:YSGG laser irradiation on root canal walls: a scanning electron microscopic and thermographic study. J Endod. 2001;27(1):9–12.
52. Takeda FH, et al. A comparative study of the removal of smear layer by three endodontic irrigants and two types of laser. Int Endod J. 1999;32(1):32–9.
53. Wang X, et al. Effects of diode laser irradiation on smear layer removal from root canal walls and apical leakage after obturation. Photomed Laser Surg. 2005;23(6):575–81.
54. da Costa Ribeiro A, et al. Effects of diode laser (810 nm) irradiation on root canal walls: thermographic and morphological studies. J Endod. 2007;33(3):252–5.
55. Kaitsas V, et al. Effects of Nd: YAG laser irradiation on the root canal wall dentin of human teeth: a SEM study. Bull Group Int Rech Sci Stomatol Odontol. 2001;43(3):87–92.
56. Goya C, et al. Effects of pulsed Nd:YAG laser irradiation on smear layer at the apical stop and apical leakage after obturation. Int Endod J. 2000;33(3):266–71.
57. Wilder-Smith P, et al. Effect of ND:YAG laser irradiation and root planing on the root surface: structural and thermal effects. J Periodontol. 1995;66(12):1032–9.
58. Takeda FH, et al. Effect of Er:YAG laser treatment on the root canal walls of human teeth: an SEM study. Endod Dent Traumatol. 1998;14(6):270–3.
59. Biedma BM, et al. Comparative study of root canals instrumented manually and mechanically, with and without Er:YAG laser. Photomed Laser Surg. 2005;23(5):465–9.
60. Altundasar E, et al. Ultramorphological and histochemical changes after Er,Cr:YSGG laser irradiation and two different irrigation regimes. J Endod. 2006;32(5):465–8.
61. Kimura Y, Wilder-Smith P, Matsumoto K. Lasers in endodontics: a review. Int Endod J. 2000;33(3):173–85.
62. Asnaashari M, Safavi N. Disinfection of contaminated canals by different laser wavelengths, while performing root canal therapy. J Lasers Med Sci. 2013;4(1):8–16.
63. Whitters CJ, et al. The bactericidal activity of pulsed Nd-YAG laser radiation in vitro. Lasers Med Sci. 1994;9:297–303.
64. Moshonov J, et al. Nd:YAG laser irradiation in root canal disinfection. Endod Dent Traumatol. 1995;11(5):220–4.
65. Walsh LJ. The current status of low level laser therapy in dentistry. Part 2. Hard tissue applications. Aust Dent J. 1997;42(5):302–6.
66. Zach L, Cohen G. Pulp response to externally applied heat. Oral Surg Oral Med Oral Pathol. 1965;19:515–30.
67. Nammour S, et al. External temperature during KTP-Nd:YAG laser irradiation in root canals: an in vitro study. Lasers Med Sci. 2004;19(1):27–32.
68. George R, Walsh LJ. Performance assessment of novel side firing safe tips for endodontic applications. J Biomed Opt. 2011;16(4):048004.
69. Bergmans L, et al. Bactericidal effect of Nd:YAG laser irradiation on some endodontic pathogens ex vivo. Int Endod J. 2006;39(7):547–57.
70. Mathew J, et al. Viability and antibacterial efficacy of four root canal disinfection techniques evaluated using confocal laser scanning microscopy. J Conserv Dent. 2014;17(5):444–8.
71. Konopka K, Goslinski T. Photodynamic therapy in dentistry. J Dent Res. 2007;86(8):694–707.
72. Komerik N, MacRobert AJ. Photodynamic therapy as an alternative antimicrobial modality for oral infections. J Environ Pathol Toxicol Oncol. 2006;25(1–2):487–504.
73. Gursoy H, et al. Photodynamic therapy in dentistry: a literature review. Clin Oral Investig. 2013;17(4):1113–25.
74. Okamoto H, Iwase T, Morioka T. Dye-mediated bactericidal effect of He-Ne laser irradiation on oral microorganisms. Lasers Surg Med. 1992;12(4):450–8.
75. Dobson J, Wilson M. Sensitization of oral bacteria in biofilms to killing by light from a low-power laser. Arch Oral Biol. 1992;37(11):883–7.
76. Chiniforush N, et al. Clinical approach of high technology techniques for control and elimination of endodontic microbiota. J Lasers Med Sci. 2015;6(4):139–50.
77. Tennert C, et al. Effect of photodynamic therapy (PDT) on Enterococcus faecalis biofilm in experimental primary and secondary endodontic infections. BMC Oral Health. 2014;14:132.
78. Rios A, et al. Evaluation of photodynamic therapy using a light-emitting diode lamp against Enterococcus faecalis in extracted human teeth. J Endod. 2011;37(6):856–9.
79. Siddiqui SH, Awan KH, Javed F. Bactericidal efficacy of photodynamic therapy against Enterococcus faecalis in infected root canals: a systematic literature review. Photodiagnosis Photodyn Ther. 2013;10(4):632–43.
80. Lee MT, Bird PS, Walsh LJ. Photo-activated disinfection of the root canal: a new role for lasers in endodontics. Aust Endod J. 2004;30(3):93–8.
81. Bonsor SJ, Pearson GJ. Current clinical applications of photo-activated disinfection in restorative dentistry. Dent Update. 2006;33(3):143–4. , 147–50, 153
82. Bago I, et al. Antimicrobial efficacy of a high-power diode laser, photo-activated disinfection, conventional and sonic activated irrigation during root canal treatment. Int Endod J. 2013;46(4):339–47.
83. Dickers B, et al. Temperature rise during photo-activated disinfection of root canals. Lasers Med Sci. 2009;24(1):81–5.

84. Kuzekanani M, Walsh LJ, Yousefi MA. Cleaning and shaping curved root canals: Mtwo vs ProTaper instruments, a lab comparison. Indian J Dent Res. 2009;20(3):268–70.
85. Haapasalo M, et al. Irrigation in endodontics. Br Dent J. 2014;216(6):299–303.
86. Caron G, et al. Effectiveness of different final irrigant activation protocols on smear layer removal in curved canals. J Endod. 2010;36(8):1361–6.
87. George R, Rutley EB, Walsh LJ. Evaluation of smear layer: a comparison of automated image analysis versus expert observers. J Endod. 2008;34(8):999–1002.
88. Peters OA, et al. Disinfection of root canals with photon-initiated photoacoustic streaming. J Endod. 2011;37(7):1008–12.
89. Pedulla E, et al. Decontamination efficacy of photon-initiated photoacoustic streaming (PIPS) of irrigants using low-energy laser settings: an ex vivo study. Int Endod J. 2012;45(9):865–70.
90. Zhu X, et al. Comparison of the antibacterial effect and smear layer removal using photon-initiated photoacoustic streaming aided irrigation versus a conventional irrigation in single-rooted canals: an in vitro study. Photomed Laser Surg. 2013;31(8):371–7.
91. Al Shahrani M, et al. Enhanced removal of Enterococcus faecalis biofilms in the root canal using sodium hypochlorite plus photon-induced photoacoustic streaming: an in vitro study. Photomed Laser Surg. 2014;32(5):260–6.
92. Balic M, et al. The efficacy of photon-initiated photoacoustic streaming and sonic-activated irrigation combined with QMiX solution or sodium hypochlorite against intracanal E. faecalis biofilm. Lasers Med Sci. 2016;31(2):335–42.
93. George R, Walsh LJ. Thermal effects from modified endodontic laser tips used in the apical third of root canals with erbium-doped yttrium aluminium garnet and erbium, chromium-doped yttrium scandium gallium garnet lasers. Photomed Laser Surg. 2010;28(2):161–5.
94. Gulabivala K, et al. The fluid mechanics of root canal irrigation. Physiol Meas. 2010;31(12):R49–84.
95. Boutsioukis C, et al. Formation and removal of apical vapor lock during syringe irrigation: a combined experimental and computational fluid dynamics approach. Int Endod J. 2014;47(2):191–201.
96. Boutsioukis C, et al. The effect of needle-insertion depth on the irrigant flow in the root canal: evaluation using an unsteady computational fluid dynamics model. J Endod. 2010;36(10):1664–8.
97. Boutsioukis C, Lambrianidis T, Kastrinakis E. Irrigant flow within a prepared root canal using various flow rates: a computational fluid dynamics study. Int Endod J. 2009;42(2):144–55.
98. de Groot SD, et al. Laser-activated irrigation within root canals: cleaning efficacy and flow visualization. Int Endod J. 2009;42(12):1077–83.
99. Matsumoto H, Yoshimine Y, Akamine A. Visualization of irrigant flow and cavitation induced by Er:YAG laser within a root canal model. J Endod. 2011;37(6):839–43.
100. Verhaagen B, Fernandez Rivas D. Measuring cavitation and its cleaning effect. Ultrason Sonochem. 2016;29:619–28.
101. Blanken J, et al. Laser induced explosive vapor and cavitation resulting in effective irrigation of the root canal. Part 1: a visualization study. Lasers Surg Med. 2009;41(7):514–9.
102. De Moor RJ, et al. Laser induced explosive vapor and cavitation resulting in effective irrigation of the root canal. Part 2: evaluation of the efficacy. Lasers Surg Med. 2009;41(7):520–3.
103. George R, Chan K, Walsh LJ. Laser-induced agitation and cavitation from proprietary honeycomb tips for endodontic applications. Lasers Med Sci. 2015;30(4):1203–8.
104. Wanner S, et al. Low-energy shock waves enhance the susceptibility of staphylococcal biofilms to antimicrobial agents in vitro. J Bone Joint Surg Br. 2011;93(6):824–7.
105. Gnanadhas DP, et al. Successful treatment of biofilm infections using shock waves combined with antibiotic therapy. Sci Rep. 2015;5:17440.
106. Boutsioukis C, et al. Evaluation of irrigant flow in the root canal using different needle types by an unsteady computational fluid dynamics model. J Endod. 2010;36(5):875–9.
107. George R, Walsh LJ. Apical extrusion of root canal irrigants when using Er:YAG and Er,Cr:YSGG lasers with optical fibers: an in vitro dye study. J Endod. 2008;34(6):706–8.
108. George R, Chan K, Walsh LJ. Modifying laser induced shock waves for use in clinical endodontics. In: The 9th World Association of Laser Therapy Congress. Bologna: Medimond International Proceedings; 2013.
109. Hmud R, et al. Cavitational effects in aqueous endodontic irrigants generated by near-infrared lasers. J Endod. 2010;36(2):275–8.
110. Hmud R, Kahler WA, Walsh LJ. Temperature changes accompanying near infrared diode laser endodontic treatment of wet canals. J Endod. 2010;36(5):908–11.
111. Deleu E, Meire MA, De Moor RJ. Efficacy of laser-based irrigant activation methods in removing debris from simulated root canal irregularities. Lasers Med Sci. 2015;30(2):831–5.
112. Moffitt JM, et al. Prediction of tetracycline-induced tooth discoloration. J Am Dent Assoc. 1974;88(3):547–52.
113. Kim ST, Abbott PV, McGinley P. The effects of Ledermix paste on discolouration of mature teeth. Int Endod J. 2000;33(3):227–32.
114. Walsh LJ, Athanassiadis B. Endodontic aesthetic iatrodontics. Australas Dent Pract. 2007;18:62–4.
115. Thomson AD, et al. Tooth discolouration: staining effects of various sealers and medicaments. Aust Endod J. 2012;38(1):2–9.
116. Walsh LJ, Verheyen P. Bleaching – accelerated with the laser. In: Moritz A, et al., editors. Oral laser application. Berlin: Quintessence; 2006.
117. Chou K, George R, Walsh LJ. Effectiveness of different intracanal irrigation techniques in removing intracanal paste medicaments. Aust Endod J. 2014;40(1):21–5.
118. Kustarci A, et al. Efficacy of laser-activated irrigants in calcium hydroxide removal from the artificial grooves in root canals: an ex vivo study. Photomed Laser Surg. 2016;34(5):205–10.
119. Chen BK, George R, Walsh LJ. Root discolouration following short-term application of steroid medicaments containing clindamycin, doxycycline or demeclocycline. Aust Endod J. 2012;38(3):124–8.
120. Chen BK, George R, Walsh LJ. Discoloration of roots caused by residual endodontic intracanal medicaments. ScientificWorldJournal. 2014;2014:404676.
121. Bennett ZY, Walsh LJ. Factors affecting the rate of oxidation and resultant discolouration of tetracyclines contained in endodontic medicaments and irrigants. Int Endod J. 2015;48(4):373–9.
122. De Moor RJ, et al. Insight in the chemistry of laser-activated dental bleaching. ScientificWorldJournal. 2015;2015:650492.
123. Walsh LJ, Liu JY, Verheyen P. Tooth discolouration and its treatment using KTP laser-assisted tooth whitening. J Oral Laser Appl. 2004;4:7–20.
124. Kuzekanani M, Walsh LJ. Quantitative analysis of KTP laser photodynamic bleaching of tetracycline-discolored teeth. Photomed Laser Surg. 2009;27(3):521–5.
125. Bennett ZY, Walsh LJ. Efficacy of LED versus KTP laser activation of photodynamic bleaching of tetracycline-stained dentine. Lasers Med Sci. 2015;30(7):1823–8.
126. Bennett ZY, Walsh LJ. Effect of photo-fenton bleaching on tetracycline-stained dentin in vitro. J Contemp Dent Pract. 2015;16(2):126–9.
127. Whitters CJ, et al. A clinical study of pulsed Nd: YAG laser-induced pulpal analgesia. J Dent. 1995;23(3):145–50.
128. Orchardson R, Peacock JM, Whitters CJ. Effects of pulsed Nd:YAG laser radiation on action potential conduction in nerve fibres inside teeth in vitro. J Dent. 1998;26(5–6):421–6.
129. Orchardson R, Whitters CJ. Effect of HeNe and pulsed Nd:YAG laser irradiation on intradental nerve responses to mechanical stimulation of dentine. Lasers Surg Med. 2000;26(3):241–9.
130. Zeredo JL, et al. Effects of low power Er:YAG laser on the tooth pulp-evoked jaw-opening reflex. Lasers Surg Med. 2003;33(3):169–72.
131. Zeredo JL, et al. Antinociceptive effect of Er:YAG laser irradiation in the orofacial formalin test. Brain Res. 2005;1032(1–2):149–53.

132. LJ W. Membrane-based photoacoustic and biostimulatory applications in clinical practice. Australas Dent Pract. 2006;17:62–4.
133. Peres F, Felino A, Carvalho JF. Analgesic effect of 904-nm laser radiation (IR) in oral surgery. Rev Port Estomatol Cir Maxilofac. 1985;26(3):205–17.
134. Mezawa S, et al. The possible analgesic effect of soft-laser irradiation on heat nociceptors in the cat tongue. Arch Oral Biol. 1988;33(9):693–4.
135. Tsuchiya K, et al. Diode laser irradiation selectively diminishes slow component of axonal volleys to dorsal roots from the saphenous nerve in the rat. Neurosci Lett. 1993;161(1):65–8.
136. Baxter GD, et al. Effects of low intensity infrared laser irradiation upon conduction in the human median nerve in vivo. Exp Physiol. 1994;79:227–34.
137. Kurumada F. A study on the application of Ga-As semiconductor laser to endodontics. The effects of laser irradiation on the activation of inflammatory cells and the vital pulpotomy. Ohu Daigaku Shigakushi. 1990;17:233–44.
138. Walsh LJ. The current status of low level laser therapy in dentistry. Part 1. Soft tissue applications. Aust Dent J. 1997;42(4):247–54.
139. Yadav P, et al. Comparative evaluation of Ferric Sulfate, Electrosurgical and Diode Laser on human primary molars pulpotomy: an "in-vivo" study. Laser Ther. 2014;23(1):41–7.
140. Marques NC, et al. Low-level laser therapy as an alternative for pulpotomy in human primary teeth. Lasers Med Sci. 2015;30(7):1815–22.
141. Gupta G, et al. Laser pulpotomy-an effective alternative to conventional techniques: a 12 months clinicoradiographic study. Int J Clin Pediatr Dent. 2015;8(1):18–21.
142. Uloopi KS, et al. Clinical evaluation of low level diode laser application for primary teeth pulpotomy. J Clin Diagn Res. 2016;10(1):ZC67–70.
143. Nammour S, et al. Comparative study on dogs between CO2 laser and conventional technique in direct pulp capping. Rev Belge Med Dent (1984). 2009;64(2):81–6.
144. Walsh LJ. Clinical evaluation of dental hard tissue applications of carbon dioxide lasers. J Clin Laser Med Surg. 1994;12(1):11–5.
145. Yazdanfar I, Gutknecht N, Franzen R. Effects of diode laser on direct pulp capping treatment: a pilot study. Lasers Med Sci. 2015;30(4):1237–43.
146. Komabayashi T, Ebihara A, Aoki A. The use of lasers for direct pulp capping. J Oral Sci. 2015;57(4):277–86.
147. Cengiz E, Yilmaz HG. Efficacy of Erbium, Chromium-doped:Yttrium, Scandium, Gallium, and Garnet Laser Irradiation Combined with Resin-based Tricalcium Silicate and Calcium Hydroxide on Direct Pulp Capping: A Randomized Clinical Trial. J Endod. 2016;42(3):351–5.
148. Walsh LJ, Ryan PC. Management of external root resorption by carbon dioxide laser ablation and sealing. Aust Endod Newsl. 1992;18:15–7.
149. Buchelt M, et al. Erb:YAG and Hol:YAG laser osteotomy: the effect of laser ablation on bone healing. Lasers Surg Med. 1994;15(4):373–81.
150. Paghdiwala AF. Root resection of endodontically treated teeth by erbium: YAG laser radiation. J Endod. 1993;19(2):91–4.
151. Angiero F, et al. Apicoectomies with the erbium laser: a complementary technique for retrograde endodontic treatment. Photomed Laser Surg. 2011;29(12):845–9.
152. Lietzau M, et al. Apicoectomy using Er:YAG laser in association with microscope: a comparative retrospective investigation. Photomed Laser Surg. 2013;31(3):110–5.
153. Bodrumlu E, et al. Temperature variation during apicectomy with Er:YAG laser. Photomed Laser Surg. 2012;30(8):425–8.
154. Dutch Working party Infection Prevention (WIP). Infection prevention when using laser instruments [website] Dec 2003 [Cited 2007 Nov]; WIP: [Available from: http://www.wip.nl].
155. Piccione PJ. Dental laser safety. Dent Clin N Am. 2004;48(4):795–807. v.
156. Andersen E, Aars H, Brodin P. Effects of cooling and heating of the tooth on pulpal blood flow in man. Endod Dent Traumatol. 1994;10(6):256–9.
157. Nyborg H, Brannstrom M. Pulp reaction to heat. J Prosthet Dent. 1968;19(6):605–12.
158. Powell GL, Morton TH, Whisenant BK. Argon laser oral safety parameters for teeth. Lasers Surg Med. 1993;13(5):548–52.
159. Armengol V, Jean A, Marion D. Temperature rise during Er:YAG and Nd:YAP laser ablation of dentin. J Endod. 2000;26(3):138–41.
160. Glockner K, et al. Intrapulpal temperature during preparation with the Er:YAG laser compared to the conventional burr: an in vitro study. J Clin Laser Med Surg. 1998;16(3):153–7.
161. Capelli A, et al. In vitro evaluation of the thermal alterations on the root surface during preparation with different Ni-Ti rotary instruments. Braz Dent J. 2004;15(2):115–8.
162. Eriksson JH, Sundstrom F. Temperature rise during root canal preparation–a possible cause of damage to tooth and periodontal tissue. Swed Dent J. 1984;8(5):217–23.
163. Walters JD, Rawal SY. Severe periodontal damage by an ultrasonic endodontic device: a case report. Dent Traumatol. 2007;23(2):123–7.
164. Barkhordar RA, et al. Evaluation of temperature rise on the outer surface of teeth during root canal obturation techniques. Quintessence Int. 1990;21(7):585–8.
165. Bailey GC, et al. Ultrasonic condensation of gutta-percha: the effect of power setting and activation time on temperature rise at the root surface - an in vitro study. Int Endod J. 2004;37(7):447–54.
166. Lee FS, Van Cura JE, BeGole E. A comparison of root surface temperatures using different obturation heat sources. J Endod. 1998;24(9):617–20.
167. Weller RN, Koch KA. In vitro radicular temperatures produced by injectable thermoplasticized gutta-percha. Int Endod J. 1995;28(2):86–90.
168. Lee BS, et al. Thermal effect and morphological changes induced by Er:YAG laser with two kinds of fiber tips to enlarge the root canals. Photomed Laser Surg. 2004;22(3):191–7.
169. Schoop U, et al. The impact of an erbium, chromium:yttrium-scandium-gallium-garnet laser with radial-firing tips on endodontic treatment. Lasers Med Sci. 2009;24(1):59–65. Epub 2007 Nov 20.
170. Eriksson AR, Albrektsson T. Temperature threshold levels for heat-induced bone tissue injury: a vital-microscopic study in the rabbit. J Prosthet Dent. 1983;50(1):101–7.
171. Gutknecht N, et al. Long-term clinical evaluation of endodontically treated teeth by Nd:YAG lasers. J Clin Laser Med Surg. 1996;14(1):7–11.
172. Machida T, et al. Study on temperature raising in tooth structure at irradiating Er:YAG laser. J Jpn Endod Assoc. 1996;17:38–40.
173. Machida T, et al. Root canal preparation using the second harmonic KTP:YAG laser: a thermographic and scanning electron microscopic study. J Endod. 1995;21(2):88–91.
174. Sauk JJ, et al. Expression of heat stress proteins by human periodontal ligament cells. J Oral Pathol. 1988;17(9–10):496–9.
175. Kimura Y, et al. Root surface temperature increase during Er:YAG laser irradiation of root canals. J Endod. 2002;28(2):76–8.
176. Theodoro LH, et al. Effect of ER:YAG and diode laser irradiation on the root surface: morphological and thermal analysis. J Periodontol. 2003;74(6):838–43.
177. Kane SA. Introduction to physics in modern medicine. London/New York: Talyor & Francis; 2003.
178. Moriyama EH, et al. Optothermal transfer simulation in laser-irradiated human dentin. J Biomed Opt. 2003;8(2):298–302.

9