Laser Fiber-Optic Modifications and Their Role in Endodontics

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ABSTRACT

A major issue when lasers are used in endodontics is achieving the correct distribution of energy in the root canal. Conventional fiber designs emit energy in the forward direction, with a divergence of approximately 20°. More recently, fibers have been developed with conical tips to achieve a wider distribution of laser energy. Since 2008, a number of alternative designs of the fiber-optic tips for endodontics have been developed which give greater lateral emissions. Such fibers have been used for diagnosing the presence of bacteria and biofilms in the root canal. They can also be used with pulsed erbium lasers to generate shockwaves in aqueous fluids. These shockwaves, directed on the walls of the root canals and also into lateral canals, deltas, and isthmus areas, can activate EDTA and provide enhanced removal of the smear layer. Because the tips have little forward emission, the risk of extruding irrigation fluids past the root canal apex is no greater than when conventional irrigation needles are used in the root canal. A further advantage of these lateral-emitting tip designs is that they do not require complex movements or withdrawal patterns to achieve even irradiation of the root canal walls. Using such conical fibers for diagnostic applications is also possible.

KEYWORDS

Modified laser fibers, endodontics, shockwaves

APPLICATION OF LASERS IN ENDODONTICS

Photothermal laser disinfection of the root canal has been reported in the literature. Even though erbium lasers exert bactericidal effects, the disinfecting action achieved in the root canal can be inconsistent when the energy is delivered through conventional fibers, which have a forward emission with a divergence angle of 18 to 20 degrees. Reports have documented the inability of erbium lasers with plain-ended, conventional fibers to reduce bacteria within the canal. When using plain fibers it is difficult to attain all of the mechanical objectives of root canal preparation without the risks of zipping (ledge formation) or perforations. Plain fibers deliver little laser energy onto the walls of the root canals, which results in inconsistent ablation. Adding to this difficulty is that plain fibers with forward emission and relatively small divergence require the clinician to move the fiber at a constant rate in a plunging, withdrawing, and rotating action to attempt to gain even irradiation of the canal walls.

INTRODUCTION

The highly complex and variable nature of the root canal system makes the achievement of the primary goals of endodontic treatment difficult, and hence modern endodontic methods employ a wide range of instruments, techniques, and medicaments to remove debris from and reduce bacteria within infected root canals, and to shape the canals to facilitate their later obturation.

The action of lasers used in endodontics is dependent on the absorption of the laser energy into chromophores such as water, apatite minerals, and various pigmented substances. As approximately 65% of the volume of bacteria is water, water-absorbing lasers can have a powerful disinfecting action via their photothermal effects on bacteria. Strong absorption in water can produce photomechanical effects such as the generation of shockwaves through cavitation. Mid-infrared lasers, like Er:YAG and Er,Cr:YSGG lasers, are well-suited for ablation of dental hard and soft tissues, and show great promise for endodontic applications because of their strong absorption in water. Clinically, the use of erbium lasers as an adjunct or alternative to conventional hand or rotary instrumentation has not yet been adopted widely, primarily because of the concerns regarding the limitations of optical delivery systems (Does the laser energy reach all parts of the canal?), thermal stresses at the level of the root surface during laser treatment (Will the periodontal ligament be adversely affected?), and the containment of both laser energy and its actions within the confines of the root canal system (Will the laser energy or its effects have unintended consequences outside the canal?).
Recently there has been increasing interest in using erbium lasers to generate shockwaves in water-based fluids, through cavitation events which follow the strong absorption of laser energy.

By causing intense agitation, the erbium laser-generated shockwaves (LGS) enhance the action of root canal irrigants, including ethylene diamine tetraacetic acid (EDTA), to provide effective removal of dense smear layers. Laser activation of solutions occurs primarily by photomechanical and photothermal mechanisms, rather than by photochemical or photodynamic processes. For endodontic irrigants, the alkaline- or acid-etching effects of irrigants are enhanced by agitation of the fluids in the canal. This agitation allows better penetration of fluids into the nooks and crannies of the complex root canal anatomy. An increase in temperature will also occur, which will accelerate chemical reactions such as etching and dissolution of proteins. Increased fluid temperature has previously been shown to increase the efficiency of sodium hypochlorite (NaOCl). With near- and mid-infrared lasers, some level of temperature increase in the fluid will occur, and this will contribute to the overall effect, above and beyond the effect caused by LGS. The ability of LGS to debride the canal depends upon the efficiency of the energy absorption within the fluid; the energy, shape, and duration of the laser pulse; and the power density achieved at the fiber tip. Changing the shape of the fiber tip influences the direction of the shockwaves so that they can be predominantly targeted onto the walls of the root canal. In contrast, the LGS produced by a plain fiber primarily travels in a forward direction, and thus is largely parallel to the walls of the root canal surface to be ablated, resulting in lower efficiency.

The following technical issues influence the selection of systems for LGS-based methods in endodontics:

1. For effective LGS using aqueous fluids, the laser wavelength chosen must be absorbed in water. LGS have been shown with erbium (Er:YAG and Er,Cr:YSGG), 940- and 980-nm diode, and Nd:YAG lasers. For the diode lasers, the LGS effect can be enhanced by including a low concentration of hydrogen peroxide in the fluid. This changes the absorption profile, and also generates a secondary cavitation bubble from the production of oxygen.

2. A conventional plain fiber tip will deliver laser energy primarily in a forward direction (parallel to the fiber tip), with limited lateral emissions (Figure 1).

3. The flexibility of fiber-optic delivery systems (regardless of the material used) reduces as their diameter increases. Furthermore, fibers require a larger arc to attain a degree of flexibility comparable to that of nickel titanium (NiTi) instruments, thus making fibers stiffer and more difficult to use in highly curved canals.

4. High transmission losses are seen with fiber optics used with erbium lasers. Passage of laser energy through fiber optics can undergo attenuation, which may be dependent on the absorption characteristics of the fiber. In the mid-infrared range, quartz glass fibers have a much lower transmissibility than sapphire. Tran reported that quartz fibers transmit very poorly at wavelengths above 2.5 microns, thus for an Er:YAG laser only 30% of the laser power can be transmitted through a quartz tip which is 12 mm long. For wavelengths in the mid-infrared regions, conventional quartz glass fibers may be used, provided a doping agent such as fluoride or germanium is included to increase the transmission efficiency of the fiber.
5. Fiber diameter influences the requirement for minimal preparation before the fiber can be inserted to the required point. At the present time, 200-micron fibers are commonly used, hence canals need to be widened to the minimum size of an ISO #20 file before the fiber can be used safely in the root canal.

6. Fibers with a plain end have right angles at their tips which tend to bind onto the canal walls, and restrict the smooth movement of the fiber toward the apex in curved canals.\(^{13}\)

7. Unlike stainless steel hand endodontic files, optical fiber tips cannot be precurved to the canal shape. The tendency of the fiber to return to its lowest energy position (i.e., being straight) forces it to push against the canal wall, giving an inherent risk of ledges or perforations during withdrawal of a flexible fiber. Such fibers will straighten past the curve, and the emitted energy will be delivered directly onto the location on the wall of the canal that has the least curvature.

8. Conventional plain optical fibers, unlike hand or rotary endodontic instruments, have parallel sides, which makes them prone to frictional binding in the canal, particularly in the apical third of the canal.

The ablative effect of lasers on hard tissues such as dentin is influenced by a number of factors, including water film thickness, pulse energy, beam diameter, and pulse duration.\(^{38-41}\) Current erbium laser systems have pulse durations which can be classified as long pulse (e.g., above 500 microseconds), short pulse (typically 200–400 microseconds), and very short pulse (less than 200 microseconds). In addition, the LGS effect and the pattern of ablation are both influenced by the shape of the fiber tip. Fiber tips with sculpted polished ends and greater lateral emissions have been developed in an attempt to overcome some of the problems related to plain fiber designs.\(^{52-54}\)

FIBER OPTICS AND THEIR MODIFICATIONS

For a laser to be useful in endodontics, it must be able to effectively deliver laser energy to the root canal of both anterior and posterior teeth. Early laser delivery systems were too bulky or cumbersome to use in the posterior parts of the oral cavity. Fiber optics were introduced into medicine in 1954 by Hopkins and Kapany,\(^{45}\) some six years before the laser was invented by Maiman. Optical fibers work by total internal reflection, and in general comprise three concentric layers. Light passes only through the central glass core of the fiber. This is surrounded by a cladding, which has a lower refractive index than the core. The cladding layer may be doped with different materials, such as fluoride, to alter its refractive index.\(^{44}\) The outer layer is the buffer layer and is used only for mechanical strength and protection of the fiber. The buffer coating is normally a polymer material such as polyvinylchloride.

The tip can also be modified by fixing certain materials to the interface of the bare quartz tip, the etchant, and the inorganic solvent.\(^{49-51}\) Alternatively, the fiber end can be polished. A flat surface can be polished at an angle to accommodate a totally reflecting surface for a unidirectional side-firing fiber. If the fiber tip is rotated while being polished at a small angle, a tapered tip will result, with multidirectional emissions.\(^{55}\)

The tip can also be modified by fixing certain materials to the fiber end to disperse the light across wide angles. Such tips are commonly called isotropic tips and are widely used in photodynamic therapy.\(^{56}\) However, these tips can only be used at relatively low energy levels.

Chemical Etching

A typical chemical etching process involves immersing a fiber-optic tip into a solution of etchant covered with an insoluble organic solvent. The chemical composition most commonly used for etching is 40-50% hydrofluoric acid (HF), topped with silicone oil. The oil not only prevents emissions of harmful HF vapors, but also modifies the contact angle between the fiber and the etchant, and thereby influences the initial meniscus height formed at the interface of the bare quartz tip, the etchant, and the inorganic solvent.\(^{20}\) Inorganic solvents including isooctane, 1-bromodecane, and 1-octenethiol\(^{57}\) may be used as alternatives to silicone oil. Etching is typically done in polystyrene containers which are chemically resistant to HF.

Fibers can also be fabricated from a range of nonglass crystalline materials, including rare earth oxides and minerals such as sapphire, as well as from ceramics or polymers.

For use with lasers emitting in the mid-infrared region, a range of alternative materials has been used that transmit well at wavelengths beyond 2.1 microns, including chalcogenide glasses, fluoride glasses, polycrystalline metal halides, and some germanate oxides. Unfortunately, these materials tend to be very difficult to manufacture, have limited flexibility, are prone to degradation in the presence of water, and have inferior mechanical and durability properties when compared to fused silica.\(^{50}\) Although quartz tips have high transmission losses in the infrared range, their better physical properties make them the popular choice for delivering laser energy within the root canal.

METHODS OF MODIFYING FIBER TIPS

Fiber tips are commonly modified by pulling or by chemical etching.\(^{13,14}\) Alternatively, the fiber end can be polished. A flat surface can be polished at an angle to accommodate a totally reflecting surface for a unidirectional side-firing fiber. If the fiber tip is rotated while being polished at a small angle, a tapered tip will result, with multidirectional emissions.\(^{15}\)

The tip can also be modified by fixing certain materials to the fiber end to disperse the light across wide angles. Such tips are commonly called isotropic tips and are widely used in photodynamic therapy.\(^{16}\) However, these tips can only be used at relatively low energy levels.
The chemical etching method is the simplest and most inexpensive method of shaping the tip to obtain a conical end which gives a broad distribution of energy, while still allowing for high optical transmission (Figure 2). There are several different methods within which etching is used to modify fibers, including static and dynamic etching and tube etching, which is used for polymer-coated materials. Tube etching relies on a microconvection mechanism for impermeable coatings, and on gradients and lateral diffusion for permeable coatings.

Modified Tip Profiles

Two important factors that influence the characteristics of the laser energy passing through any fiber are the refractive index of the fiber material and the diameter of the fiber. The geometry and optical properties of fibers define their possible applications. Clarkin et al. and Verdaasdonk et al. have described various shaped tips (e.g., ball-ended, tapered, shielded, metal-coated). Such modifications in shape lead to variations in the emission profile, opening up new applications. For example, Shoji et al. described a conical tip with a fan-shaped emission profile, delivering 80 percent of the energy laterally, and only 20 percent in the forward direction, while Heisterkamp et al. used cylindrical diffusion tips for coagulating solid tumors, however their size (diameter 1.65 mm) is too large for endodontic applications.

Ideally, lasers to be used in endodontics for smear layer removal, canal shaping, and disinfection should employ fiber-optic tips which are side-firing so that they can deliver laser energy laterally on the canal walls. The tip design should also prevent unwanted effects of the laser past the apical foramen. Spherical and cylindrical tips with a near-360-degree emission profile (isotropic tips) have been used for photoactivated disinfection of root canals using low-intensity visible red light, but the designs are not suited to delivering high-intensity pulses in the near (780-1400 nm) and mid-infrared (1400-3000 nm) range. An alternative method of achieving a 360-degree emission profile is using embedded titanium dioxide which can disperse near-infrared laser energy laterally along the length of the fiber tip, however such tips are expensive and are too large (0.6 mm) for clinical use in endodontics.

In previous work, we have reported the fabrication of conical and patterned conical (honeycomb) tips by using etching and abrasion methods in various combinations, as well as safe-tipped variants of the same technology. These “safe” tips used silver plating to reduce emission of laser energy in the forward direction. Such fiber tip surface modifications increase emissions onto the walls of the root canal, and allow for greater control of the LGS effect created by cavitation events which occur along the surface of the tip. For example, conical honeycomb tips with safe ends can activate fluids placed in the root canal and generate shockwaves that are directed onto the walls of the root canals and also into lateral canals, deltas, and isthmus areas. Such tips have little forward emission, which eliminates the problems of driving fluids past the apical foramen. A further advantage of these tip designs is that they are simpler to use in practice because it is no longer necessary for the operator to follow complex sequences of moving and withdrawing the fiber in order to achieve even irradiation of the canal walls, as is currently undertaken with conventional or radial-firing tips.

By achieving a particular design of the surface topography, the fiber surface can have improved abilities to collect light for diagnostic applications. In the case of endodontics, a side-looking fiber tip is well-suited for detecting fluorescence from bacteria and bacterial products. This characteristic can be used to find areas of incomplete preparation and can provide an endpoint to conventional biomechanical preparation. Moreover, the detection capabilities can be linked to an LGS, photothermal, or photoactivated process for removing or inactivating microorganisms and their products within the root canal. By knowing the background fluorescence levels of healthy pulpal soft tissues and noninfected dentin, such an autopilot system can be used as a locate-and-kill (LAK) device.

In terms of their therapeutic applications, modified tips which have a conical shape offer particular advantages in endodontics. The tip shape alters the LGS effect and helps guide the fiber into narrow regions of the canal (Figure 2). In 2008, George et al. reported that a conical tip could enhance the removal of the smear layer in the root canal over a conventional plain tip. The improved LGS effect obtained with either Er:YAG or Er,Cr:YSGG lasers improves the action of EDTA with Cetavlon (EDTAC) and other aqueous irrigants.

An obvious concern with the LGS method of enhanced debridement is the possibility of fluid extrusion from the apex. This risk is somewhat greater with plain-tipped fibers than with fibers with conical ends because of the forward-moving LGS generated by the former, whereas the LGS from a conical tip have a greater lateral and reduced forward effect. In a laboratory study we showed that using either conical- or plain-tipped fibers with Er:YAG or Er,Cr:YSGG lasers can drive microdroplets of fluids past the apex, particularly when the apical foramen is wide; however the volumes of extruded fluid generated were the same or less that those from using conventional irrigating needles to irrigate the same canals. One would be more interested in the potential problem of apical extrusion if shockwaves are being generated by the laser in NaOCl rather than in EDTA, because of the more irritating nature of the former.
Recently, a variation on the LGS concept known as photon-initiated photoacoustic streaming (PIPS) has been introduced, which uses more rigid, short conical tips as opposed to flexible tips with long conical ends, as was originally described by our group. This method places the tip end into the canal orifice rather than into the middle or apical thirds of the canal, and produces shockwaves in a solution of EDTA and NaOCl to enhance the removal of the smear layer and disinfection of the root canal. An issue with this method is that an Er:YAG laser with very short pulse durations (for example, less than 200 microseconds) will create an intense LGS effect, hence the fluid in the canal needs to be replenished very frequently during the treatment so that the canal does not dry out, which would lead to adverse thermal effects. With considerable flaring of the canal orifice, as is done prior to PIPS, the forward/apical vector of the LGS in the fluid will be enhanced, and so one would expect greater fluid extrusion through the apical foramen; however to date there have been no studies of apical displacement of fluid during PIPS. Recently Pedullà et al. reported no significant benefit in the use of PIPS-activated NaOCl over the use of NaOCl alone to disinfect the root canal. This reported limitation and the possibility of apical displacement of fluid with PIPS tips will undoubtedly be topics of future studies.

CONCLUSIONS

The ability to modify fiber optics to alter the emission patterns has led to a number of recent improvements in how lasers can be used to augment aspects of endodontic treatment. Modifications of fiber ends to make them side-firing and end-safe can be undertaken, giving the clinician a choice of LGS actions to suit the case under treatment. The ultimate aims of fiber modifications are to improve the removal of the smear layer and debris and to reliably detect and eliminate microorganisms from the root canal space.

AUTHOR BIOGRAPHIES

Dr. Roy George is a senior lecturer and has been the discipline lead for endodontics at the School of Dentistry and Oral Health at Griffith University since 2008. He completed his master’s degree in endodontics from India before undertaking his PhD under the supervision of Professor Laurence Walsh at the University of Queensland. Dr. George holds an adjunct position at the University of Queensland School of Dentistry, where he is a member of the lasers in dentistry research group. He has a particular interest in laser applications in endodontics and in dental materials science. He is currently the chief editor of the International Journal of Dental Clinics and a Member of the Royal Australasian College of Dental Surgeons (Endodontics). Dr. George may be contacted by e-mail at drroygeorge@gmail.com.

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Disclosures: Together Drs. George and Walsh co-developed a fiber-optic surface modification technology for endodontic diagnosis which is referred to in this paper (U.S. patent application number 13/127453, application date November 3, 2009, publication number 20110217665, publication date September 8, 2011). This has been licensed by the University of Queensland to Biolase Inc. Over the past two decades, Dr. Walsh has served as a clinical trainer for laser users for many manufacturers of dental laser systems, including Luxar, OpusDent, Sirona, A.R.C., Fotona, Deka, Hoya, Discus, KaVo, and Biolase. Neither author holds any shares in laser manufacturers nor do they have other commercial interests to declare.


