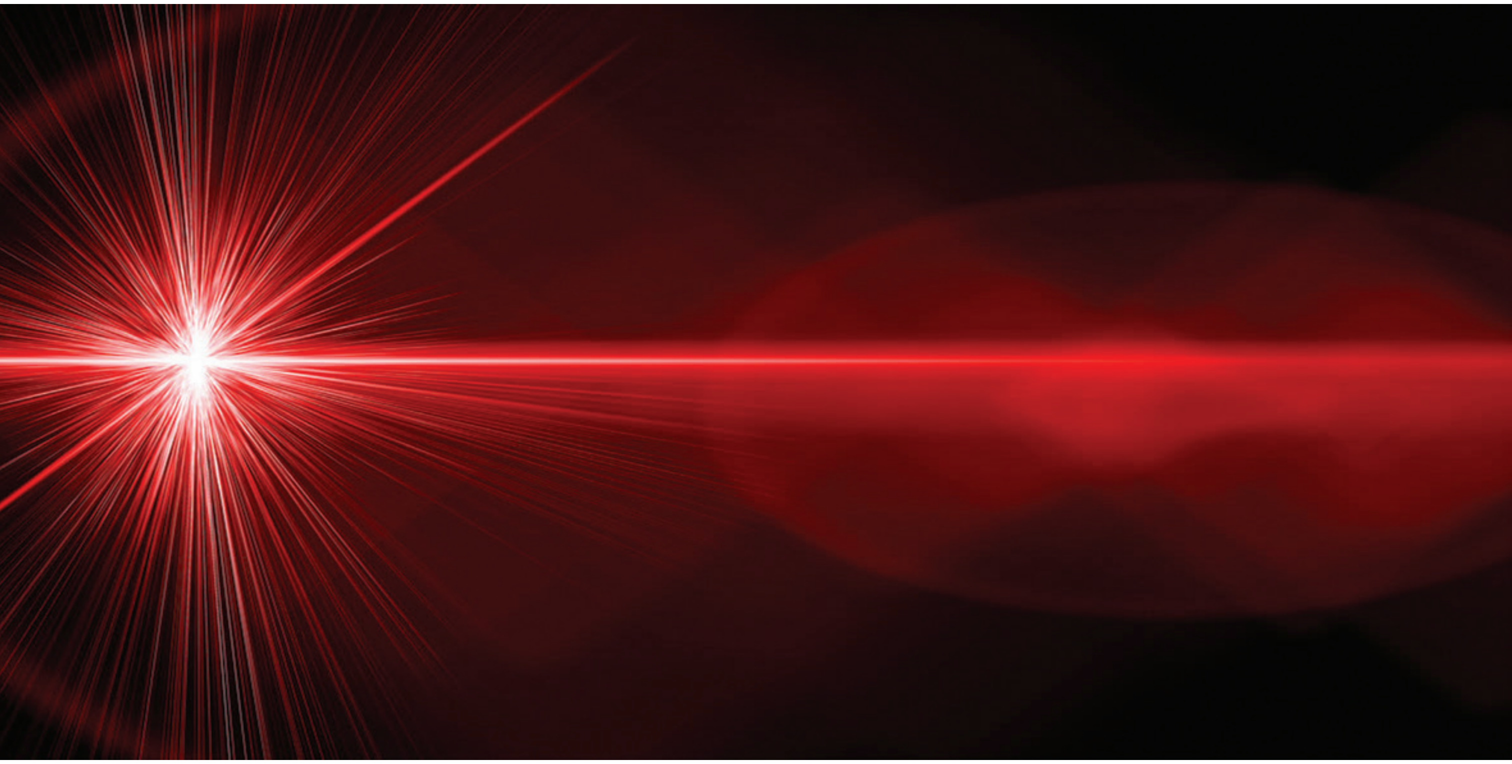
READ ME FOR CPD



New frontiers for laser-based methods for hard tissue preparation

By Emeritus Professor Laurence J. Walsh AO

All modern laser applications are based on a detailed understanding of the way that the energy interacts with the target.[1,2] As our understanding of laser-to-target interactions has grown over the years, the concepts of laser-based methods for hard tissue preparation have evolved considerably. Today we now think of mechanisms that are photothermal, photomechanical and photoacoustic in nature. This article reviews the changes in thinking in relation to dental hard tissue lasers which have occurred over the past 35 years, seen from the dual perspectives of both clinical use with patients, as well as enhancements in performance which have come from laboratory studies. It summarises what is known for the hard tissue lasers that are well-established (Figure 1) and goes beyond tooth structure ablation and laser materials processing applications (Figure 2) to discuss the latest ultra-fast laser technologies and robotic control systems (Figure 3).

The carbon dioxide laser

In the late 1980s, I became interested in how lasers could be used to assist in the care of patients with special needs, particularly those with bleeding issues or who were immunocompromised (such as solid organ transplant recipients) who needed periodontal surgery. This was the beginning of my clinical journey using lasers.[3-5] It soon became clear that using an infrared laser was an extremely effective way of performing periodontal surgery, providing a smoother patient journey during the procedure, as well as post-operatively.[5]

We quickly realised that the technology had other surgical uses beyond gingivectomies and soft tissue crown lengthening procedures. Managing external root resorption and peri-implant disease became clinical topics of interest.[6,7] Both required understanding how the laser energy would interact with either a tooth or a dental implant to ensure that adverse surface changes did not occur.[7-9] The same thinking was applied when considering how laser energy introduced into a perio pocket would interact with the adjacent structures.[10-12]

The early laser systems that we used to prepare cavities and etch enamel were large and bulky and relatively few wavelengths were available at that time to test on samples of teeth under controlled laboratory conditions. One of the most widely used surgical lasers in major hospitals at the time, the Scalibre 60, became the initial testbed for our research. This carbon dioxide laser (10600 nm wavelength) could operate in continuous wave at 60 W, or in super pulsed mode to reach peak power of around 400 W. We soon found that preparing cavities in teeth required a careful approach. When used towards the upper limits of its power range, this laser could drill holes 4 mm deep through tooth structure in 0.1 seconds. It became clear that using low powers was going to be essential and that could be advantageous not only to better control the ablation effects on the enamel and dentine, but also to reduce peripheral heating effects.[13,14]

In tests of the effectiveness of the carbon dioxide laser for cavity preparation, we noted that the shape of the cavity was the same as the imprint of the laser beam, with rounded edges (Figure 1). At these edges, the enamel had undergone fusion. In later tests, it became clear that this same laser could be used to deliberately fuse enamel, to close over the openings of very small fissures and thus serve as a method of fissure sealing. Ultrafine hydroxyapatite powder could be sintered onto the surface of the tooth (Figure 2) and this provided a novel approach to sealing fissures in teeth.[15,16] Raman spectroscopic studies of the fused enamel showed that it was not chemically the same as normal enamel, but had instead been converted by heat into beta tricalcium phosphate (TCP) and calcium hydroxide. Both materials are intensely white in colour. Beta TCP was found to be difficult to etch and bond to and its intensely white appearance would be a problem for restorations built upon it.[17,18]

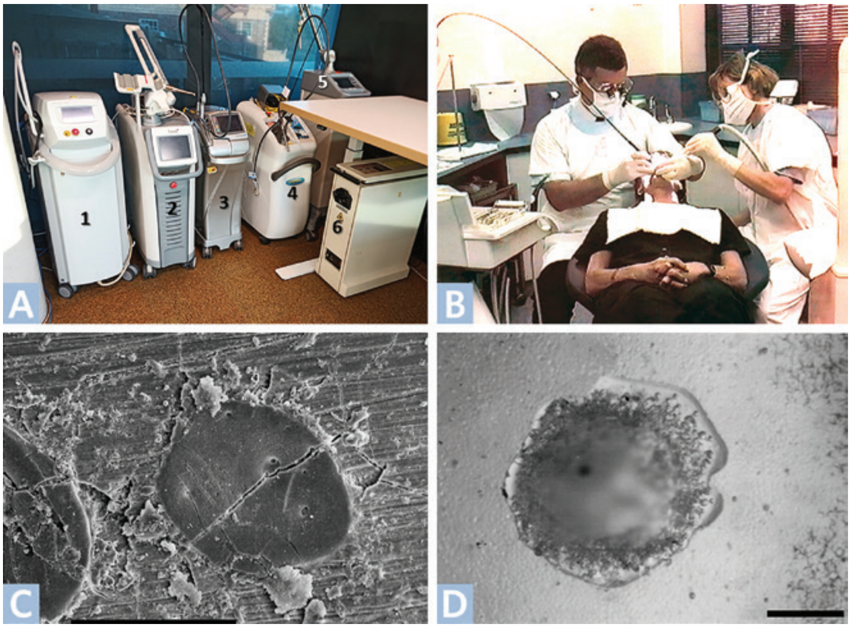


Figure 1. A: A collection of dental hard tissue lasers - Er:YAG (1 = KaVo KEY3+, 2 = Fotona Lightwalker), Er,Cr:YSGG (3 = Biolase Waterlase, 4 = Biolase); Carbon dioxide (5 = Deka Smart US-20); Nd:YAG (6 = Sunrise dLase 300). B: Using a carbon dioxide laser (Luxar LX-20D) for a procedure in 1992. C: SEM image from an early study of low power CO2 laser enamel ablation using a single laser pulse, showing a smooth shallow crater in the enamel, with spalling (ejection) of material beyond the crater edge and a central crack from thermal changes. The bar shows 100 µm. D: SEM image of the same laser parameters used on unfilled resin sealant, showing a smooth deep crater with minimal spalling at the edges. The bar shows 100 µm.

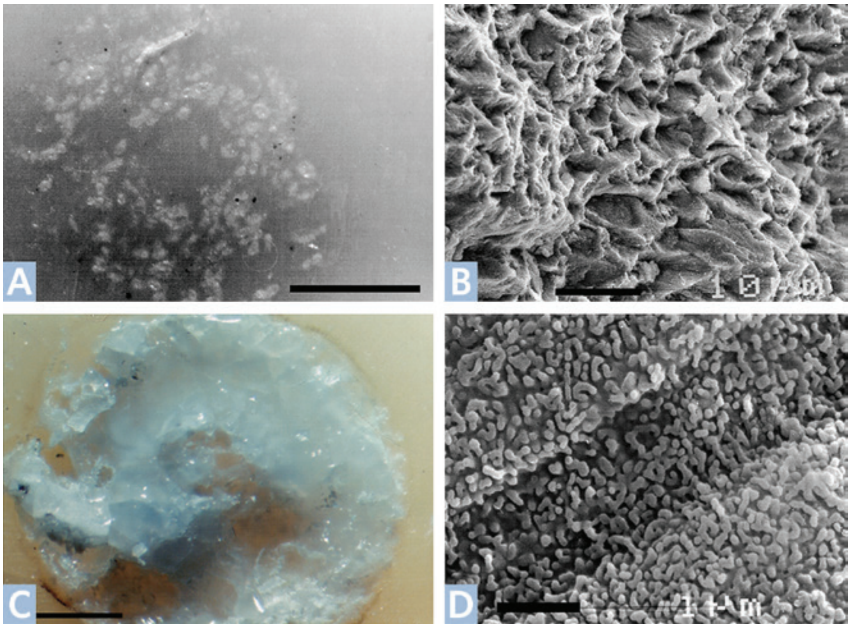


Figure 2. Carbon dioxide laser materials processing effects relevant to dental hard tissue applications. A: A light microscopic view (black and white image) showing surface roughening (laser etching) of enamel using multiple laser pulses. The bar shows 1 mm. The scale is similar to panel C immediately below it. B: SEM view of laser etched enamel showing the characteristic microscale roughness that is created. The bar represents 10 µm. C: Light microscopic view of fusion of enamel using multiple laser pulses. Note the change in colour to dense white due to chemical conversions. The bar shows 1 mm. D: Laser sintering of nanoparticles of hydroxyapatite using laser pulses to fuse the particles into a solid mass. The bar shows 1 µm.

Along the way, we discovered that both surfaces treated with the carbon dioxide laser during cavity preparation and those that had been exposed to fluoride gel prior to exposure to the laser had an unusually high resistance to acid challenges. Enamel exposed to the laser in combination with a fluoride gel also showed a much greater uptake of fluoride than normal enamel. This effect of laser activated fluoride became incorporated into the ADA item code 121. In later studies, we found that many visible light wavelengths were also able to enhance the interaction of fluoride with enamel and that the action spectrum of the effect also extended into the near and middle infrared range.[19,20] It turned out that the process of enhancing the resistance of the tooth structure to acid involved multiple mechanisms, with the main one being enhanced conversion of the surface to fluorapatite.[21]

Solid state lasers

One of the early solid state lasers we explored for hard tissue preparation was the Nd:YAG laser. The emissions from this laser did not absorb strongly into dentine or enamel, requiring the use of an initiating agent (such as India ink) to enhance its uptake into tooth structure. Careful use of this laser could however achieve some interesting and useful effects on the tooth surface, such as closing over the openings of patent dental tubules to treat hypersensitive cervical dentine.[22] We found the same beneficial effect on open dentine tubules with the Er:YAG laser.[23]

As it turned out, the Nd:YAG laser (1064 nm), the Er:YAG laser (2940 nm) and the Er,Cr:YSGG laser (2780 nm) were excellent for inducing analgesia at the level of the dental pulp, providing patient comfort during hard tissue preparation.[24,25] Both of the erbium family lasers were highly effective at ablating tooth structure using a photomechanical process involving explosions of the water trapped within the tooth structure. They could also selectively remove many types of tooth-coloured restorative materials.[26] The generation of an analgesic effect from the laser during cavity preparation made these lasers especially useful in children and in patients with significant dental fear. Undertaking laser hard tissue preparation was now a completely different patient experience for them, with little or no discomfort during the procedure and limited or no use of injections of local anaesthetic. The combination of laser induced analgesia with a different sensory experience gave superior patient outcomes and drove the uptake of this technology in private practice settings.[27,28]

Etching and bonding

In the 1990s, we were interested in the process of physical conditioning of the surface to enhance the adhesion of materials. We worked with some early generation dual wavelength lasers from Fotona such as the Twinlight that combined both an Nd:YAG laser and the Er:YAG laser in the one unit. As we did not have access to one of these systems in Brisbane on a regular basis, but did have access to our own CO_2 lasers, those became the workhorse for studies of laser etching of enamel and dentine.

> "An important advantage of the Ho:YAG laser over the erbium laser wavelength is that the former can be delivered using a flexible glass fibre, while the erbium lasers require more complex delivery systems..."

We found that when using the bonding agents available at the time, the bond strength to enamel could be considerably enhanced by using laser protocols that selectively roughened the surface of the tooth.[29-31] Later, we found that the same laser could also be used to selectively remove composite resin, unfilled resin, sealants and residues of bonding agents.[32,33]

Toward more selective cavity preparations

Given the better control of tooth structure ablation with the erbium family lasers compared to the carbon dioxide laser, we then changed track and focused our efforts on optimising the process of ablation for the erbium lasers. We found there was a very straightforward relationship between the pulse energy delivered from the laser handpiece and the extent of ablation. Using a low pulse energy could selectively remove carious tooth structure but not sound tooth structure and also allow the selective removal of composite resin restorations.[26,34,35]

By the turn of the 21st century, erbium family lasers had become recognised for their usefulness as part of general dental practice, as an alternative to traditional rotary instruments.[26,36,37] It was also clear that cavities prepared using these lasers had reduced microleakage at their margins.[38]

Over time, several methods were developed to help guide laser removal of dental caries from both enamel and dentine. Specific methods were needed because conventional approaches, including the use of caries detector dye, lacked sensitivity and specificity and were notorious for giving false positive results that could then lead to over-preparation.[36] One of these new methods involved analysis of the type of sound produced by pulses which caused ablation of tooth structure.[39] The science underlying this related to the tissue density difference between sound and carious tooth structure because of the presence of more water in carious tooth structure and the corresponding effects on the propagation of sound.

Another method that was developed was the use of real-time fluorescence diagnostics. This same method has been found to be useful for other dental procedures, including the debridement of teeth and dental implants and the preparation of the root canal system. As with cavity preparation, in all these situations it can provide advice around an endpoint for treatment.[9,40-46] In fact, changes in fluorescence readings over time could even predict when cavitation of white spot lesions was likely to occur.[47,48] More recent work has identified factors that could interfere with fluorescence measurements, especially those that cause false negative readings and has documented several solutions to overcoming such issues.[49-51]

As well, various wavelengths of light have been used to assess their value for fluorescence diagnosis. While early work used visible red light (655 nm) for real time feedback,[52] later work used visible violet light (405 nm). This was found to be highly effective for fluorescence recognition of both carious tooth structure and also of restorative materials.[53-58] Using fluorescence-based approaches greatly reduces the risk of over preparation of teeth when removing existing restorations.[59]

Using new wavelengths for hard tissue preparation

While the erbium laser wavelengths of 2940 and 2780 nm have been popular for some time, there are other useful wavelengths, such as the 9300 nm carbon dioxide laser (as used in the Solea® laser) and the Holmium:YAG, at 2100 nm. In 2007, we tested the Ho:YAG laser with a water mist spray and found that this could give excellent ablation of both enamel and dentine, providing results very similar to that seen for the erbium laser wavelengths.[60] An important advantage of the Ho:YAG laser over the erbium laser wavelength is that the former can be delivered using a flexible glass fibre, while the erbium lasers require more complex delivery systems.

> "Another method that was developed was the use of real-time fluorescence diagnostics. This same method has been found to be useful for debridement of teeth and implants and the preparation of the root canal system..."

Looking to the future, a major area of interest will be laser systems that can deliver minimal intervention approaches, encompassing the treatment of patients across a wide range of ages.[61-64] Such systems should be able to ablate all manner of materials that may be present on teeth and within teeth. This aspect is a major limitation of existing commercial laser systems for dental hard tissues.[65] To achieve this objective means thinking outside the box and looking towards ultrashort pulse laser systems, especially those that operate in the near infrared range (e.g. 700-1300 nm). In this wavelength range, the ablation of all manner of materials can be achieved. At the same time, laser analgesia can be generated by photobiomodulation.[65]

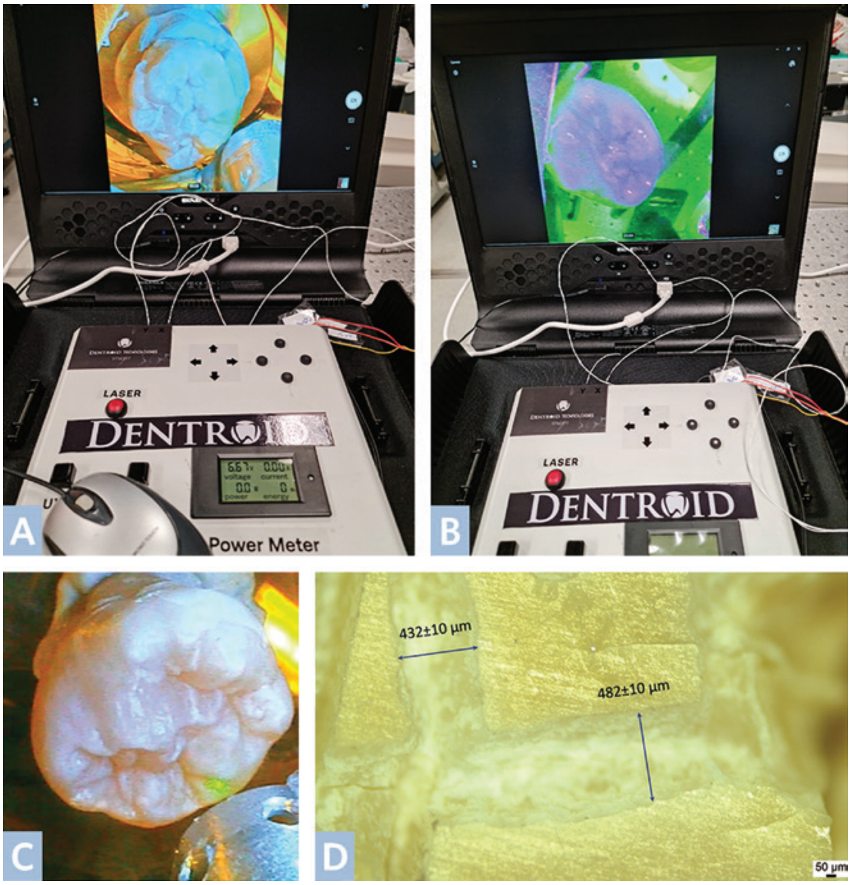


Figure 3. Hard tissue procedures conducted on the bench using the Dentroid® prototype device. A and B: Views of the operator's control station for the laser, showing micromanipulator controls for variable speed X-Y translation of laser cutting and laser power monitoring. The screen displays images of the treated tooth, using different fluorescence imaging modes. C: The working view of the same tooth seen under white light illumination. Images A-C are courtesy of Emudent Technologies. D: An example of precision laser cutting of dentine using the Dentroid® prototype device, showing a vertical channel 430 microns wide and a horizontal channel 482 microns wide. These were prepared using a robotically controlled pulsed Ho:YAG 2100 nm laser using water mist spray. Note the smooth and regular margins and the lack of thermal changes (melting, carbonisation and spalling) of the target. The scale bar in the lower right corner is 50 microns. Image D is courtesy of Ludovic Rapp, Steve Madden and Andrei Rode of the Laser Physics Centre, Research School of Physics, Australian National University, Canberra.

Lasers with ultrashort pulses achieve the highest peak powers when the pulse duration is in the femtosecond (10^{-15} of a second) range. By using an extremely short pulse duration, these lasers can create massive energy density values within targets of all types, regardless of whether or not they are opaque or transparent to the laser wavelength being used. Femtosecond lasers can alter the surface of the material, as well as work inside the material, through the creation of nanoplasma. The effects of nanoplasma on materials include ionisation and disruption of chemical bonds, achieving ablation with minimal heat associated changes or defects occurring beyond the target.[66-69]

By using an ultrashort laser with high pulse frequencies, a machining action can be achieved on a structure to achieve unrivalled precision in terms of preparation geometry. Current femtosecond laser systems can generate ablation rates up to a quarter of that of a high-speed edge turbine drill in sound enamel. Around the world, work in multiple laboratories has explored the performance of femtosecond laser systems for dental hard tissue ablation, with the goal of making these laser systems not only more precise, but equal to traditional rotary dental instruments in terms of their overall speed. Thus far, very promising results have been obtained from over 10 studies undertaken by different groups around the world, including in Australia.[70-80] In fact, Australian researchers have been at the forefront of the field of ultrashort laser pulse shaping of dense and rigid materials for the past 15 years.[66,67,71]

Including a feedback system with an ultrashort pulse laser system will maximise the benefits of the high precision of the femtosecond laser approach, allowing the stepwise removal of restorations of all types as well as selective removal of carious tooth structure. In addition to this, an ultrashort laser system could be combined with a robotic system so that the laser beam could be controlled remotely by the dentist - sitting in the same room or at a distant location - rather than being hand held, as is the case with current dental hard tissue lasers. This hands-off approach would reduce the physical demands of performing restorative dental procedures, including intense visual concentration during cavity preparation and could also assist in reducing health issues relating to musculoskeletal disorders and posture. A device which operates at a distance from the dentist would also reduce exposure of the dentist to aerosols generated by the procedure.

As well as being able to complete cavity preparations, femtosecond laser systems can also perform subtle forms of etching known as nanoripples, which can enhance the adhesion of materials for bonding to the tooth structure and they can also be used to undertake photo-polymerisation, using two photon effects that accompany ultrashort laser pulses. This would allow the deposition and selective curing of materials in thin layers, which would be advantageous in reducing or eliminating effects caused by shrinkage during polymerisation.

Robotically controlled femtosecond lasers

It has been argued that, despite their many advantages, one of the barriers to the wider adoption of lasers for hard tissue procedures by mainstream dentistry is that hard tissue lasers are used to prepare teeth without tactile feedback. They do not have the same feel as using traditional rotary instruments. As well, pulsed lasers cut in increments. Using large pulse energies creates irregular craters and as a result, early lasers were not very effective for tasks like minimal preparations. Fine control of the laser handpiece and overlapping of pulses is necessary to achieve regular flowing cavity outlines. This level of control is generally not possible unless magnification is being used.

Recently, an Australian company (Emudent Technologies, trading as Dentroid) developed and patented the "Dentroid®" concept for hands-free, low-contact laser dentistry. Their concept involves a miniaturised robotic assembly placed in the mouth and attached directly onto target teeth. The laser beam is delivered onto the tooth surface through miniaturised optics that are controlled by the dentist using a panel located in the operatory a few feet away or remotely. This concept can herald a new age of laser dentistry using the power of advanced imaging and real-time feedback to guide operative procedures, from minimally invasive preparations through to crown and bridge preparations, at unprecedented levels of precision that are not achievable using hand-held laser handpieces. Real time imaging using multiple imaging modes brings in superior visualisation of what is happening on the tooth as the laser energy interacts with it, but also opens the door for advanced control systems that guide the placement of laser pulses using autopilot algorithms and artificial intelligence, informing the clinician of what parts of the tooth are carious or not, which parts are restored versus sound and whether geometry of the preparation needs modification, for example. The company expects their product to be available in the market by 2024 (Figure 3).

> "The deployment of femtosecond laser systems into dental practice would be a game changer, in the same way that the use of ultrashort pulse laser systems completely changed the specialty of ophthalmic surgery and brought in completely new methods for vision correction that are less invasive..."

Conclusions

The horizons for dental hard tissue lasers see the emergence of new wavelengths and new delivery modalities, offering enhanced control for the dentist as well as enhanced visualisation of the structure and composition of the tooth which is being treated. Together, these all allow more selective dentistry with less biological cost for the patient. From the 1980s to the present, the technology has improved dramatically and the changes which have occurred have represented revolutions rather than small stepwise changes. The deployment of femtosecond laser systems into dental practice would be a game changer, in the same way that the use of ultrashort pulse laser systems completely changed the specialty of ophthalmic surgery and brought in completely new methods for vision correction that are less invasive. The lasers that we currently have available for dental hard tissue procedures could not have been imagined when this field was in its infancy in the 1980s. Likewise, one can only dare to imagine what the next decades will bring in this area of technology.

About the author

Emeritus Professor Laurence J. Walsh AO is a specialist in special needs dentistry who is based in Brisbane, where he served for 36 years on the academic staff of the University of Queensland School of Dentistry, including 21 years as Professor of Dental Science and 10 years as the Head of School. Since retiring in December 2020, Laurie has remained active in hands-on bench research work, as well as in supervising over 15 research students at UQ who work in advanced technologies and biomaterials and in clinical microbiology. Laurie has served as Chief Examiner in Microbiology for the RACDS for 21 years and as the Editor of the ADA Infection Control Guidelines for 12 years. His published research work includes over 330 journal papers, with a citation count of over 15,400 citations in the literature. Laurie holds patents in 7 families of dental technologies. He is currently ranked in the top 0.25% of world scientists. Laurie was made an Officer of the Order of Australia in January 2018 and a life member of ADAQ in 2020 in recognition of his contributions to dentistry.

References

1. Walsh LJ. Dental lasers: Some basic principles. Postgrad Dent. 1994; 4: 26-29.
2. Coluzzi DJ, Convissar RA, Roshkind DM, Walsh LJ. Laser fundamentals. In: Convissar RA (ed) Principles of Laser Dentistry, 3rd edition, 2022. St Louis: Elsevier Mosby.
3. Walsh LJ. Soft tissue management in periodontics using a carbon dioxide surgical laser. Periodontology 1992; 13:13-19.
4. Walsh LJ, Ivanovski S. Cosmetic management of gingival fibromatosis by laser recontouring. Periodontology 1997; 18(1): 3-6.
5. Walsh LJ. Utilization of a carbon dioxide laser for periodontal surgery: a three year longitudinal study. Periodontology 1995; 16: 3-7.
6. Walsh LJ, Ryan PC. Management of external root resorption by carbon dioxide laser ablation and sealing. Australian Endodontic Newsletter 1992; 18: 15-17.
7. Walsh LJ. The use of lasers in implantology: an overview. J Oral Implantol. 1992; 18: 335-340.
8. Fenelon T, Bakr M, Walsh LJ, George R. Effects of lasers and their delivery characteristics on machined and micro-roughened titanium implant surfaces. Bioengineering 2020; 7(3: 93-113.
9. Tran C, Walsh LJ. Novel models to manage biofilms on microtextured dental implant surfaces. In: Dhanasekaran D and Thajuddin N (eds) Microbial Biofilms. Importance and Applications. Croatia: InTech Publishers, 2016. pp. 463-486.
10. Walsh LJ. Laser curettage: a critical analysis. Periodontology 1993; 14: 4-12.
11. Walsh LJ. Applications of carbon dioxide surgical lasers in periodontology and implantology. Postgraduate Dentist (London) 1994; 4:50-54.
12. Walsh LJ. Emerging applications for lasers in implantology. Periodontology 2002; 23(1):8-15.
13. Walsh LJ. Pulpal safety parameters for irradiation of dental hard tissues with carbon dioxide lasers. Aust Endod Newsl 1993; 19: 21-25.
14. Sandford MA, Walsh LJ. Pulpal temperature changes during desensitization and other low power hard tissue CO2 laser procedures. Aust Endod Newsl. 1995; 21: 36-38.
15. Walsh LJ, Perham S. Enamel fusion using a surgical carbon dioxide laser: a technique for sealing pits and fissures. Clin Prev Dent 1991; 13: 16-20.
16. Walsh LJ. Applications of infrared lasers in preventive dentistry. Dent Today 1990; 6: 1-4.
17. Aminzadeh A, Shahabi S, Walsh LJ. Raman spectroscopic studies of CO2 laser-irradiated human dental enamel. Spectrochim Acta. 1999; 55:1303-1308.
18. Aminzadeh A, Shahabi S, Walsh LJ. FT-Raman spectroscopic studies of Nd/YAG laser-irradiated human dental enamel. Iran J Chem Chem Eng. 2002; 21(1):44-46.
19. Vlacic J, Meyers IA, Kim J, Walsh LJ. Laser-activated fluoride treatment of enamel against an artificial caries challenge: comparison of five wavelengths. Aust Dent J. 2007;52(2):101-105.
20. Vlacic J, Meyers IA, Walsh LJ. Laser-activated fluoride treatment of enamel as prevention against erosion. Aust Dent J. 2007;52(3):175-180.
21. Vlacic J, Meyers IA, Walsh LJ. Photonic conversion of hydroxyapatite to fluorapatite: a possible mechanism for laser-activated fluoride therapy. J Oral Laser Appl. 2008;8(2):95-102.
22. Forrest-Winchester K, Walsh LJ. The effect of infrared laser radiation on dentinal permeability in vitro. Periodontology 1992; 13: 37-43.
23. Shakabiae F, Diklic S, Walsh LJ. An assessment of changes in dentine permeability following irradiation with a pulsed Erbium:YAG laser. Periodontology 2002; 23(1):4-7.
24. Walsh LJ. Applications and features of current generation dental lasers used for cavity preparation. Australas Dent Pract. 2002;13(5):70-74.
25. Walsh LJ. Laser dentistry: Membrane-based photoacoustic and biostimulatory applications in clinical practice. Australas Dent Pract. 2006;17(5):62-64.
26. Walsh LJ. The current status of laser applications in dentistry. Aust Dent J. 2003;48(3):146-155
27. Walsh LJ. Laser analgesia with pulsed infrared lasers: theory and practice. J Oral Laser Appl. 2008;8(1):1-10.
28. Hmud R, Walsh LJ. Dental anxiety: causes, complications and management approaches. Internat Dent. 2007;9(5):6-16.
29. Walsh LJ, Abood D, Brockhurst PJ. Bonding of composite resin to carbon dioxide laser-etched human enamel. Dent Mat. 1994; 10: 162-166.
30. Shahabi S, Walsh LJ. Effect of bonding agents on adhesion of composite resin following CO2 laser etching of human enamel. J Clin Laser Med Surg. 1996; 14:169-173.
31. Shahabi S, Brockhurst PJ, WALSH LJ. Effect of selected tooth-related factors on the shear bond strengths obtained with CO2 laser conditioning of human dental enamel. Aust Dent J. 1997;42(2): 81-84.
32. Mazouri Z, Walsh LJ. Damage to dental composite restorations following exposure to CO2 laser radiation. J Clin Laser Med Surg. 1995; 13:73-76.
33. Smith SC, Taverne AAR, Walsh LJ. Removal of orthodontic bonding resin residues by CO2 laser radiation: surface effects. J Clin Laser Med Surg. 1999; 17(1):13-18.
34. Al-Batayneh OB, Seow WK, Walsh LJ. Assessment of Er:YAG laser for cavity preparation in primary and permanent teeth: a scanning electron microscopic and thermographic study. Pediatric Dent. 2014; 36(3):90-94.
35. Sanusi SY, Seow WK, Walsh LJ. Effects of Er: YAG laser on surface morphology of dental restorative materials. J Phys Sci. 2012; 23(2): 55-71.
36. Mount GJ, Walsh LJ, Brostek A. Instruments used in cavity preparation. In: Mount GJ and Hume WR. Preservation and restoration of teeth, 2nd edition. Brisbane, Knowledge Books and Software. 2005. pp. 119-143.
37. Brostek AM, Bochenek AJ, Walsh LJ. Minimally invasive dentistry: A review and update. Shanghai J Stomatol. 2006; 15(3):225-249.
38. Shahabi S, Ebrahimpour L, Walsh LJ. Microleakage of composite resin restorations in cervical cavities prepared by Er,Cr:YSGG laser radiation. Aust Dent J. 2008; 53(2):172-175.
39. Walsh LJ. Laser analgesia with pulsed infrared lasers: theory and practice. J Oral Laser Appl. 2008;8(1):1-10.
40. Sainsbury AL, Bird PS, Walsh LJ. DIAGNOdent laser fluorescence assessment of endodontic infection. J Endod. 2009; 35(10): 1404-1407.
41. Ho QV, George R, Sainsbury AL, Kahler WA, Walsh LJ. Laser fluorescence assessment of the root canal using plain and conical optical fibers. J Endod. 2010; 36(1):119-122.
42. Shakibaie F, George R, Walsh LJ. Applications of laser-induced fluorescence in dentistry. Int J Dent Clinics 2011; 3(2): 26-29.
43. George R, Walsh LJ. Laser-Assisted Endodontics. In: DJ Coluzzi, SP Parker (eds.), Lasers in Dentistry—Current Concepts, Textbooks in Contemporary Dentistry, Springer International Publishing: Cham, Switzerland. 2017. pp. 192-211.
44. Shakibaie F, Lamard L, Rubinzstein-Dunlop H, Walsh LJ. Application of Fluorescence Spectroscopy for Microbial Detection to Enhance Clinical Investigations. In: Britun N & Nikiforov A (Eds) Photon Counting. Croatia: InTech Publishers, 2018. pp. 225-242.
45. Walsh LJ. Caries diagnosis aided by fluorescence. In: Arkanslan Z (Ed) Dental Caries - Diagnosis and Management. Croatia: InTech Publishers, 2018. pp. 97-115.
46. Shakibaie F, Walsh LJ. Optical diagnostics to improve periodontal diagnosis and treatment. In: Manakil J (Ed) Periodontology and Dental Implantology. Croatia: InTech Publishers, 2018. pp. 73-86.
47. Walsh LJ, Groeneveld G, Hoppe V, Keles F, van Uum W, Clifford H. Longitudinal assessment of changes in enamel mineral in vivo using laser fluorescence. Aust Dent J. 2006;51(4):S26.
48. Walsh LJ, Clifford H. Changes in Diagnodent scores in smooth surface enamel carious lesions in primary teeth: a longitudinal clinical study. J Oral Laser Appl. 2008;8(3):157-164.
49. Sin JH, Hamlet S, Walsh LJ, Love RM George R. Oxidising agents and its effect on human dentine fluorescence diagnostic measurements. Photodiagn Photodyn Therapy 2020; 31:101950.
50. Sin JH, Ipe DS, Hamlet S, Walsh LJ, Love RM, George R. Fluorescence characteristics of E. faecalis in dentine following treatment with oxidizing endodontic irrigants. Photodiagn Photodyn Therapy 2021; 33:102344.
51. Tsai A, George R, Walsh LJ. Evaluation of the effect of various endodontic irrigants and medicaments on dentine fluorescence. Photodiagn Photodyn Therapy 2022; 37:102651.
52. 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(5):122-128.
53. Mandikos MN, Walsh LJ. Illuminating dental instrument, coupling and method of use. Australian patent 2010/300079 in 2014 and US patent 9,028,251 in 2015.
54. Shakibaie F, Walsh LJ. Effect of oral fluids on dental caries detection by the VistaCam. Clin Exp Dent Res. 2015; 1(2): 74-79.
55. Shakibaie F, Walsh LJ. Violet and blue light-induced green fluorescence emissions from dental caries. Aust Dent J. 2016; 61(4):464-468.
56. Kiran R, Walsh LJ, Forrest A, Tennant M, Chapman J. Forensic applications: Fluorescence properties of tooth-coloured restorative materials using a fluorescence DSLR camera. Forensic Sci Int. 2017; 273:20-28.
57. Kiran R, Chapman J, Tennant M, Forrest A, Walsh LJ. Detection of tooth-colored restorative material for forensic purposes based on their optical properties: an in vitro comparative study. J Forensic Sci. 2019; 64(1):254-259.
58. Kiran R, Chapman J, Tennant M, Forrest A, Walsh LJ. Direct tooth-colored restorative materials: a comparative analysis of the fluorescence properties among different shades. Int J Esthet Dent. 2020; 15(3):318-332.
59. Kiran R, Chapman J, Tennant M, Forrest A, Walsh LJ. Fluorescence-aided selective removal of resin-based composite restorative materials: An in vitro comparative study, J Esthet Restor Dent. 2020;32(3):310-316.
60. George R, Walsh LJ. Factors influencing the ablative potential of the Er: YAG laser when used to ablate radicular dentine. J Oral Laser Appl. 2008;8(1):33-41.
61. Walsh LJ. Minimally invasive operative techniques using high tech dentistry. Australas Dent Pract. 2006; 17(5):108-110.
62. Walsh LJ, Brostek AM. Minimal intervention dentistry principles and objectives. Aust Dent J. 2013; 58 (Suppl 1): 3-16.
63. Brostek AM, Walsh LJ. Minimal intervention dentistry in general practice. Oral Hlth Dent Managemnt. 2014; 13(2):285-294.
64. Walsh LJ. Laser applications in dentistry - the far horizon. Austral Dent Pract. 2010; 21(5): 102-104.
65. Liang R, George R, Walsh LJ. Pulpal response following photo-biomodulation with a 904-nm diode laser: a double-blind clinical study. Lasers Med Sci. 2016;31(9):1811-1817.
66. Rapp L, Gamaly EG, Guist R, Furfaro L, Lacourt PA, Dudley JM, Juodkazis S, Courvoisier F, Rode AV. Ultrafast laser-induced micro-explosion: material modification tool. OSA Techl Digest: Photon Fiber Technol. 2016: BT3B.4.
67. Rapp L, Haberl B, Bradby JE, Gamaly EG, Williams JS, et al. Selective localised modifications of Si crystal by ultrafast laser induced micro-explosion. Proc. SPIE 2013; 8607: 86070H.
68. Watanabe W, Li Y, Itoh K. Ultrafast laser micro-processing of transparent material. Optics Laser Technol. 2016; 78(A): 52061.
69. Sugioka K, Cheng Y. Ultrafast lasers—reliable tools for advanced materials processing. Light Sci Appl. 2014; 3:149.
70. Neev J, Da Silva LB, Feit MD, Perry MD, Rubenchik AM, Stuart BC. Ultrashort pulse lasers for hard tissue ablation. IEEE J Select Top Quantum Electr. 1996; 2(4):790-800.
71. Rode AV, Gamaly EG, Luther-Davies B, Taylor BT, Graessel M, Dawes JM, Chan A, Lowe RM, Hannaford P. Precision ablation of dental enamel using a subpicosecond pulsed laser. Aust Dent J. 2003; 48(4): 233-239.
72. Lizarelli RFZ, Costa MM, Carvalho-Filho E, Nunes FD, Bagnato VS. Selective ablation of dental enamel and dentin using femtosecond laser pulses. Laser Phys Lett. 2008; 5(1): 63-69.
73. Ji L, Li L, Devlin H, Liu Z, Liao J, Whitehead D. Ti:sapphire femtosecond laser ablation of dental enamel, dentine, and cementum. Lasers Med Sci. 2012; 27(1):197-204.
74. Alves SV, Oliveira V, Vilar R. Femtosecond laser ablation of dentin. J Phys D Appl Phys. 2012; 45(24): 245401.
75. Bello-Silva MS, Wehner M, Eduardo CdP, Lampert F, Poprawe R, Hermans R, Esteves-Oliviera M., Precise ablation of dental hard tissues with ultra-short pulsed lasers. Preliminary exploratory investigation on adequate laser parameters. Lasers Med Sci. 20-13; 28(1):171-184.
76. Chen H, Liu J, Li H, Ge W, Sun Y et al. Femtosecond laser ablation of dentin and enamel: relationship between laser fluence and ablation efficiency. J Biomed Opt. 2015; 20(2): 028004.
77. Le Q-T, Bertrand C, Vilar R, Femtosecond laser ablation of enamel. J Biomed Opt. 2016; 21(6): 065005.
78. Hikov T, Pecheva E, Montgomery P, Antoni F, Leong-Hoi A, Petrov T. Precise femtosecond laser ablation of dental hard tissue: preliminary investigation on adequate laser parameters. J Physics Conf Ser. 2017; 794(1): 012036.
79. Petrov T, Pecheva E, Walmsley AD, Dimov S. Femtosecond laser ablation of dentin and enamel for fast and more precise dental cavity preparation. Mat Sci Eng C. 2018; 90:433-438.
80. Loganathan S, Santhanakrishnan S, Bathe R, Arunachalam M. Prediction of femtosecond laser ablation profile on human teeth. Lasers Med Sci. 2018; 34(4): 693-701.
81. Han P, Li H, Walsh LJ, Ivanovski S. Splatters and aerosol contamination in dental aerosol generating procedures. Appl Sci. 2021; 11(4): 1914.