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Review

Biophotonics in Dentistry

Ehsaneh Daghigh Ahmadi [1,†], Saudah Hafeji [2,†], Zohaib Khurshid [3], Eisha Imran [4], Muhammad Sohail Zafar [5,6], Morvarid Saeinasab [7] and Farshid Sefat [2,8,*]

1 College of Engineering, Institute of Life Science-2, Centre for Nanohealth, Swansea University, Singleton Park, Swansea SA2 8PP, UK; e.daghighahmadi@swansea.ac.uk
2 Department of Biomedical and Electronics Engineering, School of Engineering, University of Bradford, Bradford BD7 1DP, UK; saudah.hafeji@hotmail.co.uk
3 Department of Prosthodontics and Implantology, College of Dentistry, King Faisal University, Al-Ahsa 31982, Saudi Arabia; drzohaibkhurshid@gmail.com
4 Department of Dental Materials, HITEC Dental College, Institute of Medical Sciences, Taxilla 751010, Pakistan; eishaimran.dental@hitec-ims.edu.pk
5 Department of Restorative Dentistry, College of Dentistry, Taibah University, Medina Munawwarah 42353, Saudi Arabia; drsohail_78@hotmail.com
6 Department of Dental Materials, Islamic International Dental College, Riphah International University, Islamabad 44000, Pakistan
7 Department of Biology, Faculty of Science, Ferdowsi University of Mashhad, Mashhad 9177948974, Iran; m.saeinasab@gmail.com
8 Interdisciplinary Research Centre in Polymer Science & Technology (Polymer IRC), University of Bradford, Bradford BD7 1DP, UK
* Correspondence: f.sefat1@bradford.ac.uk; Tel.: +44-(0)-1274-233679
† These authors contributed equally to this work.

Abstract: The aim of this review paper is to concentrate on the use and application of photonics in dentistry. More than one hundred review and research articles were comprehensively analysed in terms of applications of photonics in dentistry, including surgical applications, as well as dental biomaterials, diagnosis and treatments. In biomedical engineering, various fields, such as biology, chemistry, material and physics, come together in to tackle a disease/disorder either as a diagnostic tool or an option for treatment. Engineers believe that biophotonics is the application of photonics in medicine, whereas photonics is simply a technology for creating and connecting packets of light energy, known as photons. This review paper provides a comprehensive discussion of its main elements, such as photoelasticity, interferometry techniques, optical coherence tomography, different types of lasers, carbon nanotubes, graphene and quantum dots.

Keywords: biophotonics; dentistry; laser; quantum dots; graphene; carbon nanotube

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1. Introduction

In recent decades, the role of photonics in medical and biomedical applications has significantly increased, and it is as crucial as its applications in optics and optoelectronic devices. The role of photonics in medical applications, such as sensing [1,2], diagnostic imaging [3], therapy [4,5], drug delivery [6,7] and laser surgery [8], is as significant as its application in optics and electronics, such as a high-quality single photon sources [9], semiconductor technologies [10] and fibre optics telecommunications [11]. In dentistry, laser and light amplification by stimulated emission of radiation (LASER) plays a crucial role in soft tissue and periodontal applications [12]. Figure 1 illustrates dental applications of laser in the modern era in accordance to their respective speciality (oral surgery [13,14], prosthodontics [15,16], periodontics [13], endodontics [17–19] and orthodontics [13]).

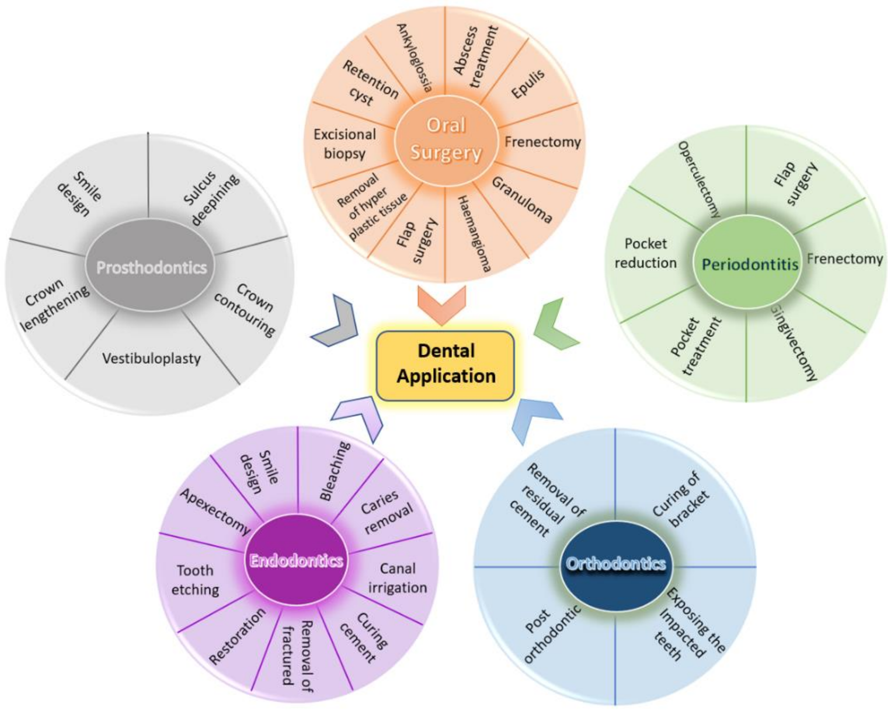

Figure 1. Dental applications of laser in the modern era in according to specialty.

Medical applications of laser in surgery date back to about 40 years ago, when CO_2 laser was invented by C. Kumar N. Patel in 1964 [20,21]. In fact, reducing the operating time and complications of surgeries are two main advantages of utilising laser in surgery [17]. Specifically, in dentistry, in addition to toxic issues of conventional procedures [22], treatment is very time-consuming and can be stressful to the patients [23]; alternatively, lasers can overcome all these disadvantages of the typical procedures [18,24–28].

In this review paper, historical events and currents advancements are discussed initially, followed by many applications in dentistry, such photoelasticity, interferometry techniques (moiré interferometry), optical coherence tomography, lasers (types of lasers, applications of lasers, peri-implantitis and regenerative laser periodontal therapy), photodynamic therapy (management of symptomatic oral lichen planus, management of chronic periodontitis in smokers and anticancer therapy) and quantum dots.

2. Historical Events and Current Advancements

Currently, different types of lasers with a wide range of wavelengths are widely utilised in medical applications, such as Ar (488–515 nm) [29], Er:YAG (2940 nm) [19,30,31], CO_2 (10,600 nm) [32] and Nd:YAG (1064 nm) [33]. In 1964, Stern and Sognnaes began their laser studies on hard dental tissues using a ruby laser with a wavelength of 694 nm [34], which was followed by applying a CO_2 laser to cut bone tissue for the first time [35]. Although the CO_2 laser had shown promising results for successful soft tissue treatment [36,37] and further studies suggested the use of Nd:YAG and CO_2 lasers considerably decreased severe irreversible damage to the pulp [38,39], it was still not an appropriate candidate for cutting mineralised tissue due to its biological complications, such as severe carbonisation effects and a delayed bone healing [40,41]. After research successes with short-pulsed infrared laser systems during the late 1980s and 1990s [42], the best results in ablation of bone and dental hard tissue were achieved by utilising a laser system operating at wavelengths of 2.9–3 µm and 5.90–6.45 µm [43]. As a result of this finding, the Er:YAG and the Er,Cr:YSGG lasers, with wavelengths of 2.94 µm and 2.78 µm, respectively, are promising candidates for laser surgery on hard and mineralised tissue [44–47]. Figure 2 summarizes the classification of lasers according to their usage and their respective wavelengths [48].

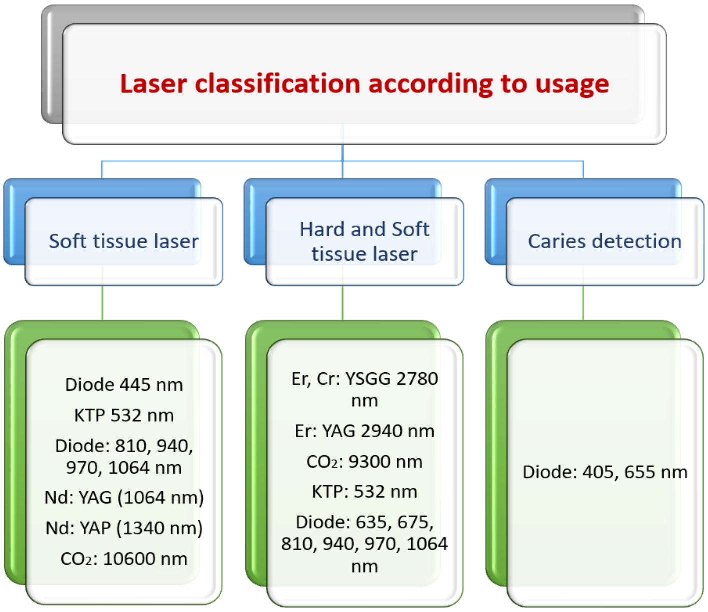

Figure 2. Classification of laser according to its usage and wavelength.

Figure 3 illustrates a broad history of laser in relation to dentistry [48].

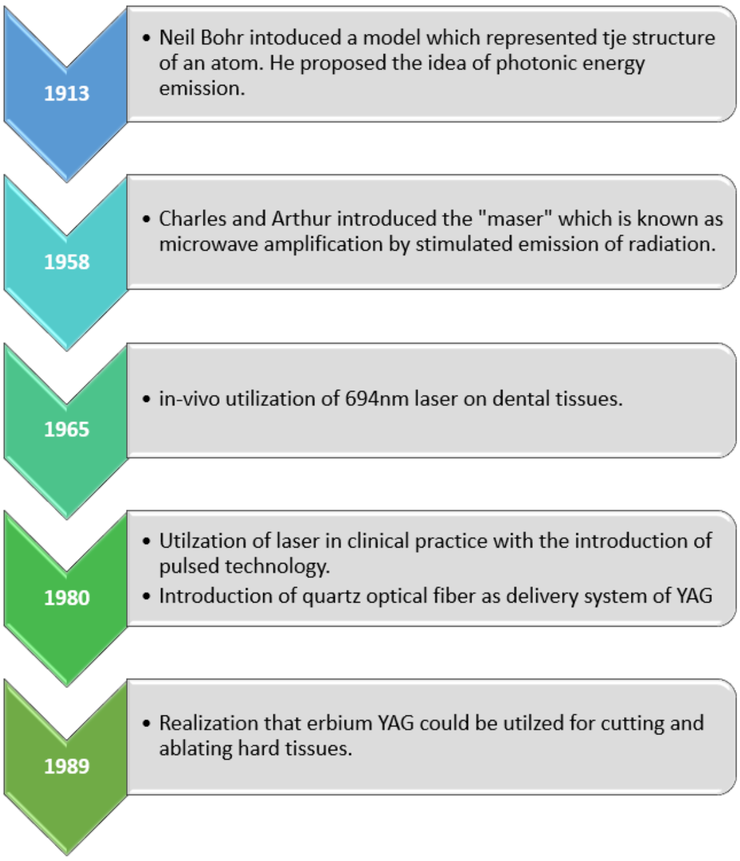

Figure 3. Timeline of lasers.

Other than laser applications in dentistry, carbon nanotubes (CNTs) have attracted attention in numerous medical applications, including as a biomaterial candidate for the purpose of tissue regeneration in dental implants, orthopaedic applications [49] and drug delivery [50], as well as applications in electronics [51], optical devices [9], and filtration [52] and sensing [53] applications. CNTs have unique optical, electrical, thermal and mechanical properties, as well as their functionalisation capability and biocompatibility, which enable an impressive capacity in medical applications, including for dental implants, drug delivery systems and as a scaffold for bone tissue engineering [54,55]. CNTs constitute some of the strongest material in nature due to their mechanical properties; as a result, by adding single-wall carbon nanotubes (SWCNTs) to hydroxyapatite structures (HY-SWCNTs), which are mainly used in maxillofacial surgery, dental/orthopaedic implants become more resistant, achieving improved biocompatibility [56,57]. In addition to enhanced biocompatibility and stronger implants, bone formation and bone-healing process are accelerated, which is specifically beneficial for diabetics who suffer from low rates bone growth [58,59]. Clinical research on diabetic and non-diabetic rats revealed that HY-SWCNTs, compared to nanocomposites, improved bone repair of tooth sockets of rats with type I diabetes [59].

In addition, quantum dot (QDs), which are nanoscale semiconductors with three-dimensional quantum confinement of charge carriers, are another popular nanomaterial in biomedical applications [60,61], particularly in florescence imaging and diagnostics [61,62], in addition to their vast applications in optoelectronics [63,64], such as solar cells [65], quantum cryptography [66], lasers [67] and LEDs [68], owing to their high quantum efficiency and unique optical and electrical properties (Figure 4). The first biomedical applications of QDs in biological detectors [69] and florescent biological labels [70] dates back to 1998, two decades after the invention of QDs by Alexey Ekimov in 1981 [71,72]. In regard to dental applications of QDs as luminophores, CdSe/ZnS core-shell semiconductor QDs were employed as resin dopant to tailor the fluorescence of dental resin composites [73]. Principally, the best colour matching between natural teeth and restoring composites is determined by their optical properties, such as light absorption, scattering and reflection. The incorporation of various sizes of QD cores into resin biomaterials results in similar fluorescence properties as those of natural human teeth, owing to the different band gap of QDs depending on their sizes [73]. Cancer diagnosis, treatment and photodynamic therapy are another biomedical application of QDs due to their ability to target and accumulate in tumours. Such applications are currently approved for various forms of cancers, including oral and lung cancers [74], owing to their high sensitivity to detect cancer cell biomarkers, as well as high permeability and retention effects.

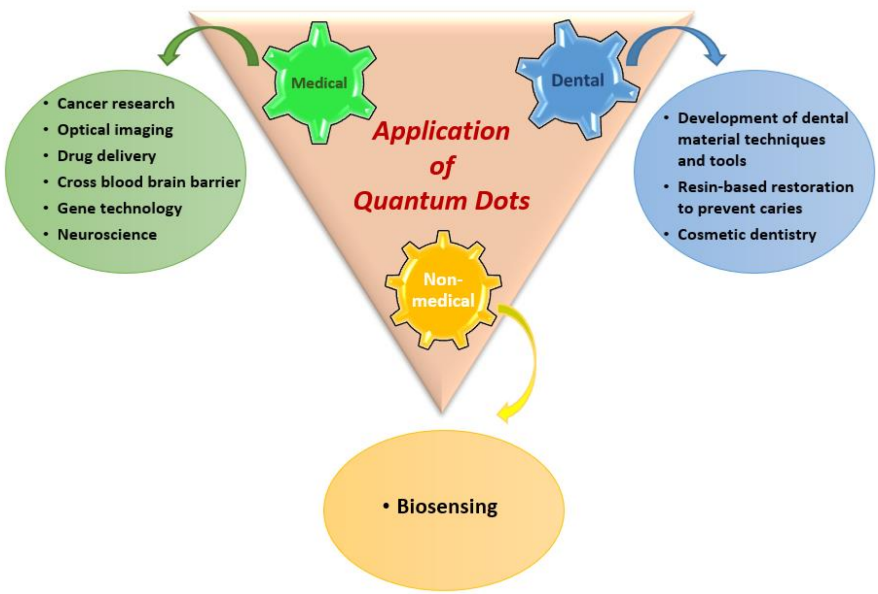

Figure 4. Applications of quantum dots in relation to dentistry.

Graphene, one-atom-tick sheets of carbon atoms are attracting much interest in a wide range of applications, such as sensors, electronics, optoelectronics and biomedical applications [75–78], due to their outstanding optical, electrical, physical and mechanical properties, such as large surface-to-volume ratio, robustness and high electrical/thermal conductivity. Their strong sensitivity to electrical perturbation makes them an excellent candidate for biosensors, in particular sensors based on field-effect transistors. Their large surface-to-volume ratio is another outstanding property that makes them a very strong candidate for drug delivery applications [79]. Graphene and its derivatives have a considerable impact in tissue engineering, particularly dental nanocomposites, owing to their ability to be functionalised with biomolecules and high mechanical strength—200 times stronger than steel. In terms of cytotoxicity, recent research confirmed that graphene oxide (GO) and graphene oxide composites, compared to other types of graphene derivations, is less cytotoxic; however its cytotoxicity depends on different parameters, including the functionalisation technique [80]. In addition, GO possesses excellent bacterial antiadhesive properties, which are a beneficial factor in the prevention of dental infection and implant surface infection [81–83].

3. Applications in Dentistry

The development of photonics has been invaluable in many dentistry applications, including but not limited to diagnostics, biomechanical studies, treatment of oral cancers and caries and the development of dental prostheses. Photonics applications remain advantageous compared to conventional techniques in that they are non-contact and non-destructive and allow for multiple nanometre-scale measurements of over large areas.

3.1. Photoelasticity

Photoelasticity is an optical characteristic that has been used for many years in experimental stress analysis. Most transparent materials exhibit a temporary birefringence property when exposed to strain and loading due to changes in molecular orientation distribution [84]. This can be utilised to study biomechanics within dentistry and various types of orthodontic movements or structural design.

A model was constructed using a transparent 'photoelastic' material, and the magnitude and direction of occlusal forces was replicated to mimic those experienced in physiological conditions. When these models were placed under stress, they exhibited birefringence, where normally incident light rays split into two parts with two refractive indices and velocities directly related to the stress at that point [85]. Analysis of the birefringence using a polariscope allows for calculation of shear stress. Plane polariscopes and circular polariscopes can be used to analyse light fringes with circular polariscopes, providing the advantage of only showing isochromatic and not isoclinic light rays.

The optical technique has been applied in dentistry for many years, dating back to 1935, when it was used to study effects of orthodontic movements on the dental alveoli [86]. It has since been used in various studies of dental biomechanics, including investigating the relationship between dental caries and stress concentrations in 1966 and two-dimensional experimental stress analysis of inlays in 1967, which improved cavity design by lowering stress concentrations [87]. In 1971, photoelasticity was used by Farah and Craig as a means of determining the stress distribution on a gold dental bridge, with the study revealing that highest stress concentrations occurred at soldered joints [88]. Brodsky, Caputo and Furstman (1975) later utilised the optical technique to develop a photoelastic model, allowing the technique to be used to study root tipping [89]. Photoelasticity has also allowed studies comparing different endodontic dowels, such as the effect of length, diameter and other design parameters on stress distributions [90]. In 2000, the photoelasticity technique was used to analyse in vivo stress and strain distributions in human dental supporting structures from the tooth root to the alveolar bones [91]. An epoxy resin model (Figure 5) was used to represent the tooth and alveolar bone, and a diffuse-light polariscope was used to observe the fringe patterns when loaded with forces applied at different axes to represent forces applied under physiological conditions.

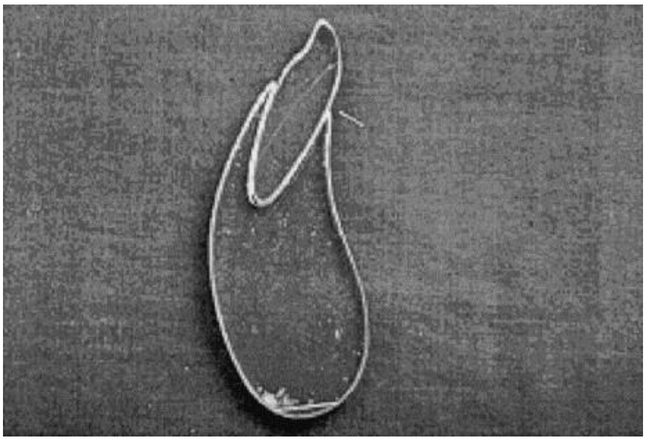

Figure 5. Model of tooth and supporting bone for photoelastic stress analysis. Strain gauge and photoelastic analysis of in vivo strain and in vitro stress distribution in human dental supporting structures. Adapted with permission from Ref. [92]. 2019, Elsevier.

The resultant fringe patterns are seen in Figure 6. Most of the stresses are distributed along the cervical and middle third of the root and supporting bone. The study highlighted the role of the periodontium in distribution of stresses and bone remodelling.

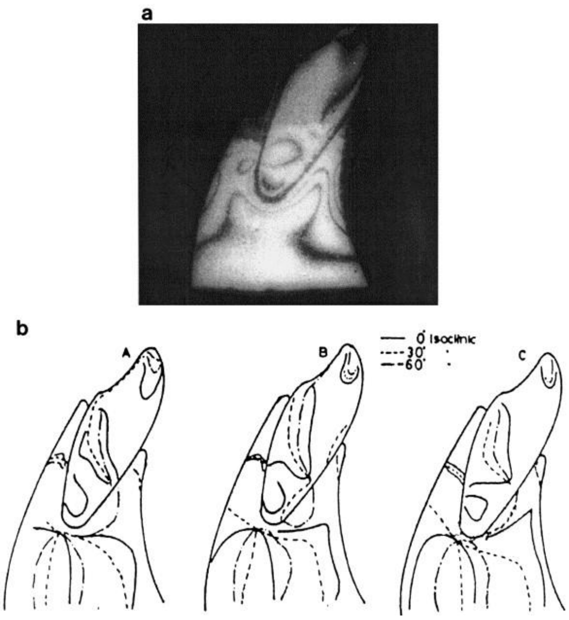

Figure 6. (**a**) Fringe pattern showing stress distribution in a tooth with normal supporting bone at a load of 225 N along its long axis. (**b**) Fringe patterns showing stress distribution when load is directed at (**A**) 0° (**B**) 30° and (**C**) 60° to the long axis. Strain gauge and photoelastic analysis of in vivo strain and in vitro stress distribution in human dental supporting structures. Adapted with permission from Ref. [92]. 2019, Elsevier.

Asundi and Kishen (2001) further investigated the stress distributions between the tooth and bone interface using photoelasticity [93]. Their study considered some limitations of the use of the photoelasticity technique in its past applications in dentistry. One such limitation is that in order to generate sufficient fringes to analyse forces much larger than normal, physiological occlusal forces must be applied. In this study, the technique was refined through the use of a circular polariscope and an image-processing system, which allowed an enhanced sensitivity and accuracy, not only allowing analysis of fringe patterns but also the ability to identify signs of fringe orders, thus improving understanding of the stress distributions.

In 2004, the effect of the morphology of occlusal surfaces on transfer of loading on the tooth apex was investigated using photoelastic methods [94]. The study concluded that the surface morphology of occlusal surfaces is a highly significant factor influencing the magnitude and direction of stress. Cehreli et al. (2004) investigated stress and strain magnitudes of different models of implants and observed the resultant isochromatic fringe patterns around the implants [95]. The study concluded butt-joint and internal-cone oral implants have similar distribution characteristics.

Over the years, the use of photoelasticity to determine the biomechanics and stress distributions of various implant designs has allowed for optimisation of dental prostheses. The technique has also been used as a means of comparison between different dental biomaterials. In 2011, Asvanund and Morgano completed a photoelastic stress analysis of different material composites of endodontic posts, including a stainless-steel post and a fibre-reinforced post with a silver amalgam or composite resin core [96]. Two-dimensional photoelastic models were utilised to stimulate root dentin, and each model was studied with two force magnitudes in two directions.

3.2. Interferometry Techniques

3.2.1. Electronic Speckle Pattern Interferometry

Electronic speckle pattern interferometry (ESPI) is a non-destructive optical technique developed in the 1970s that can also be used to investigate biomechanics in dentistry applications. Specular reflection fringe patterns from surfaces are recorded before and after a load is placed. The images before and after loading are then computed and combined to form a resultant image with a speckle pattern of fringes, allowing for calculation of three-dimensional distributions of stress and strain [97,98]. A schematic of a typical experimental setup of ESPI is shown in Figure 7 [99]. Yap, Tan and Quan (2004) considered the advantages of ESPI in terms of its capability to take high-sensitivity measurements of surfaces in a non-contact manner [100].

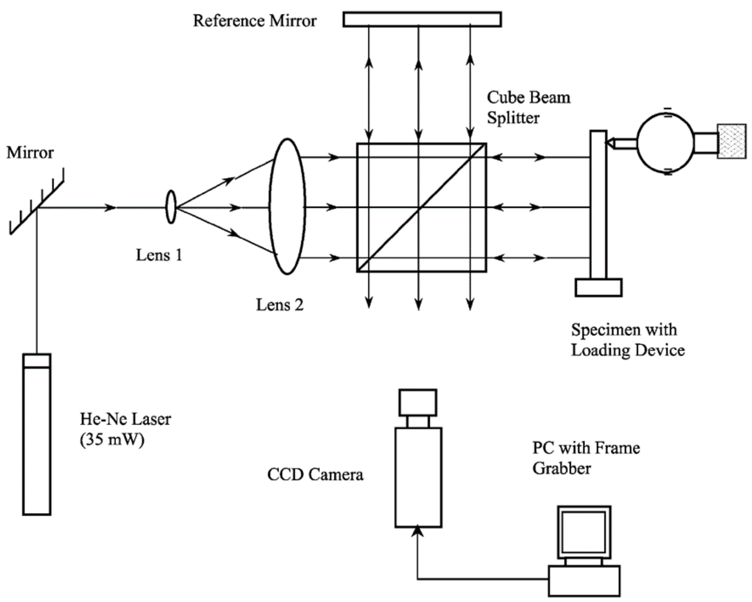

Figure 7. Schematic of experimental setup of ESPI. Non-destructive characterization of resin-based filling materials using electronic speckle pattern interferometry. Adapted with permission from Ref. [100]. 2019, Elsevier.

Applications in dentistry have included comparisons between different restorative materials, including gold, ceramic, composite resin or amalgam inlays used to fill dental cavities. The effect of the type of material on deformation of teeth when subject to loading was investigated, with results showing deformation varied depending on the type of material. Another advantageous use of ESPI in dentistry includes the development of a non-destructive test to characterise the modulus of resin-based inlays [100]. The study was significant, as such a non-destructive test would allow time-dependent effects to be determined using the same specimens, thus saving time and material. In 2009, the ESPI technique was used to compare deformation when a tooth-mandible complex was placed under load compared to an isolated tooth [101]. Minipig molars were used, and the study demonstrated that teeth bend in the direction of the load.

Other uses of ESPI include the study of dentin compression in water, where the Young's modulus of root dentin under compression was obtained. Results showed the location of the root dentin had a significant effect on the stiffness value, with root dentin from interproximal locations found to have a modulus of 21.3 GPa, whereas root dentin from buccal and lingual locations had a modulus of 15 GPa. In 2012, ESPI was used by Fages et al. as a means of gaining a greater understanding of the structure and mechanical behaviour of the dentin–enamel junction and comparing it against the dentin–ceramic junction of a crown [102]. Figure 8 shows the natural sample under loading, and Figure 8A shows the initial sample under white light. Figure 8B–D shows the typical fringes when load is applied on the sample, and the dentin–enamel junction is clearly visible (represented by red arrows). The junction becomes visible at a load of around 35.5 N.

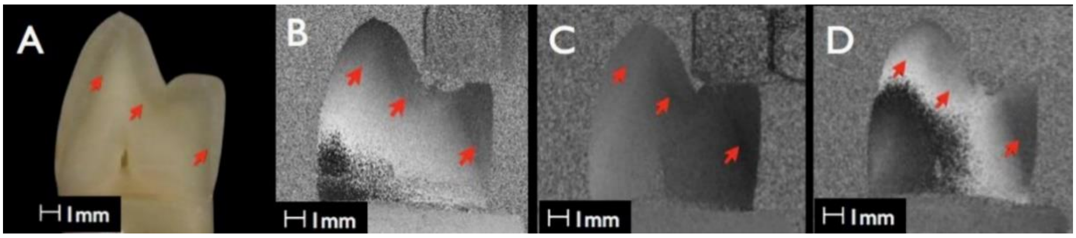

Figure 8. Natural tooth sample (**A**) under white light, (**B**) under a force of 35.5 N, (**C**) under a force of 40.23 N and (**D**) under a force of 82.54 N. Comparative mechanical behaviour of dentin enamel and dentin ceramic junctions assessed by speckle interferometry (SI). Adapted with permission from Ref. [102]. 2019, Elsevier.

In comparison, Figure 9 shows the crown under loading. The junction becomes visible under a load of 38 N and is a clear, continuous, visible line. The study was described as significant, as it demonstrates that the biomechanical behaviour of a prosthetic crown closely resembles that of a natural junction.

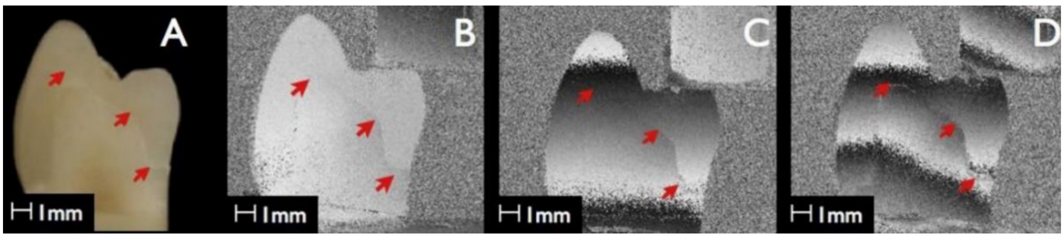

Figure 9. Prosthetic crown sample (**A**) under white light, (**B**) under a force of 36.78 N, (**C**) under a force of 77.56 N and (**D**) under a force of 64.09 N. Comparative mechanical behaviour of dentin enamel and dentin ceramic junctions assessed by speckle interferometry (SI). Adapted with permission from Ref. [103]. 2019, Elsevier.

Thermally induced deformation of human dentine was also investigated by Kishen et al. using ESPI [97]. Lower central incisor teeth were extracted, and thermal loads ranging from 25–60 °C were applied so speckle patterns could be captured and analysed. The study was significant in presenting the capability of ESPI for use in studying thermal response in materials such as dentin.

3.2.2. Moiré Interferometry

Moiré interferometry is an alternative optical method for strain analysis, with applications in many fields, including biomechanics, fracture mechanics and the study of composite materials [104]. The high sensitivity associated with moiré interferometry makes it a valuable technique for performing real-time study of the biomechanics of dental structures. The technique involves two superimposed light arrays, and the resultant interference patterns, termed moiré fringes, are analysed to provide information about mechanical behaviour. Understanding the biomechanical behaviour of dentin structures is essential in order to correctly restore any loss of mechanical integrity through dental treatments [105].

Wang and Weiner (1998) studied strain distributions in different structures of human teeth using the moiré interferometry technique [106]. Figure 10 [106] shows the resultant moiré fringe patterns. Results showed strain in enamel to be significantly lower compared to strain in dentin, with a subsequently higher elastic modulus. The study confirmed the hypothesis that dentin contains structural adaptations to withstand and transfer stress.

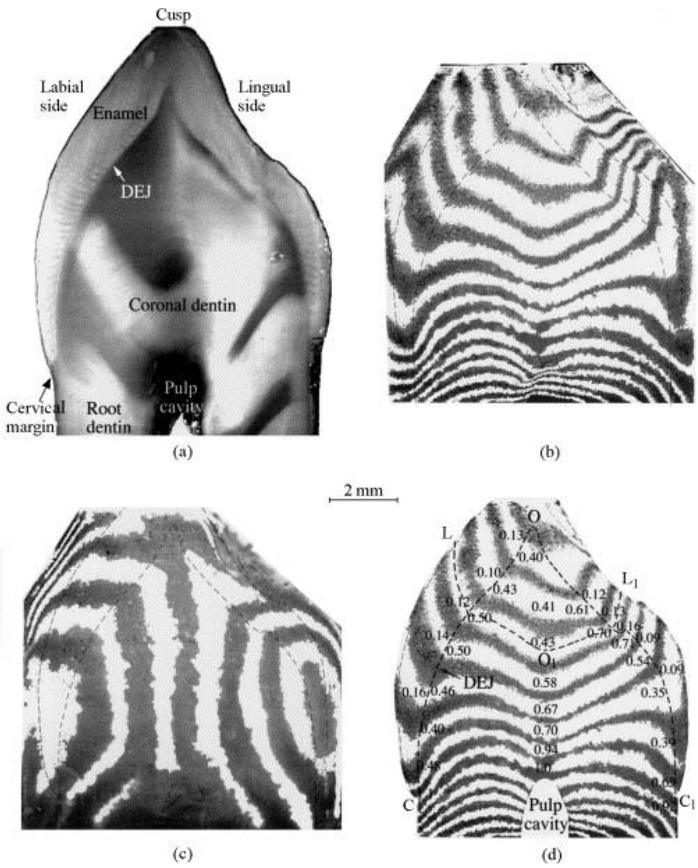

Figure 10. Canine tooth slice showing (**a**) anatomical terminology and (**b**–**d**) moiré fringe patterns obtained with a load of 500 N. Strain–structure relations in human teeth using moiré fringes. Adapted with permission from Ref. [106]. 2019, Elsevier.

In 2001, tooth deformation caused by moisture change was mapped by Wood et al. using moiré interferometry [107]. Dentin and enamel have different water contents; therefore, changes in humidity can be used to change their moisture levels and thus produce a mechanical load across the dentin–enamel junctions. Moiré interferometry was used to measure magnitudes of strain. Wide variations of strain were seen between the two samples. The study was significant in showing that the dentin–enamel junction is a unique interface that must be studied. Wood et al. stated that the full-field and high-resolution results obtained proved that moiré interferometry is a powerful tool to study deformation of materials.

More recently, digital moiré interferometric analysis was used to study the effect of bioactive biopolymeric nanoparticle surface conditioning on mechanical deformation in dentin. Specimens were loaded, moiré interferometry showed distinct patterns of deformation and the experiment successfully investigated a method of improving mechanical integrity of dentin [105].

3.3. Optical Coherence Tomography

Optical coherence tomography (OCT) is a non-invasive, non-destructive, high-resolution, cross-sectional imaging technique widely used in various clinical applications, including ophthalmology, dentistry and gastroenterology [108]. It may be considered equivalent to ultrasound imaging but with light waves instead of ultrasound. OCT is a powerful technique that captures real-time images of tissue in situ without the need for biopsies, achieving image resolution of 1–15 µm, comparable to that of optical microscopy [109].

OCT is another interferometry method using low-coherence light. A photodetector is used to capture interference of reflected and scattered light. Different systems of OCT have been developed over the years, including doppler OCR (D-OCT), polarisation-sensitive OCT (PS-OCT), spectral-domain OCT (SD-OCT) and endoscopic OCT. The applications of OCT in dentistry and other biomedical applications are vast.

OCT was first applied in dentistry in 1998 as a means of capturing in vivo images of hard and soft dental tissues [110]. The study obtained high-resolution in vitro images and was significant in showing the potential for OCT in diagnosing periodontal tissue. This was also one of the first studies to use the OCT technique to image hard tissue, and a greater understanding of the structure of teeth was achieved.

Another application of OCT in dentistry is the detection of microleakage of restorations and fillings, as well as evaluation of their integrity [109]. A quality assessment of various dental treatments using OCT was conducted by Sinescu et al. (2008) [111]. The study evaluated the use of OCT to study material defects and microleakage of dental prostheses. The applicability of OCT in this application was demonstrated successfully. Later, OCT was used as a means of investigating microleakage after endodontic treatment using lasers, and the conclusion reached was that the use of lasers improved prognosis and reduced microleakage [112].

More recently, in 2015, a study using swept-source OCT (SS-OCT) demonstrated the detection of in vivo microleakage, and the study concluded OCT to be a reliable technique for location and size analysis of a microleakage [113]. This is significant because the early detection of microleakage could prevent secondary caries that arise from accumulated bacteria stuck within microleakages. One limitation of the study was that it provided information for large-crack detection only; therefore, more research is needed on different materials and different crack sizes. Within this study, OCT was used to observe the growth of cracks and the resultant damage to a ceramic/enamel interface under fatigue shear testing [113]. Figure 11 [113] shows the images of the ceramic/enamel interface obtained via OCT.

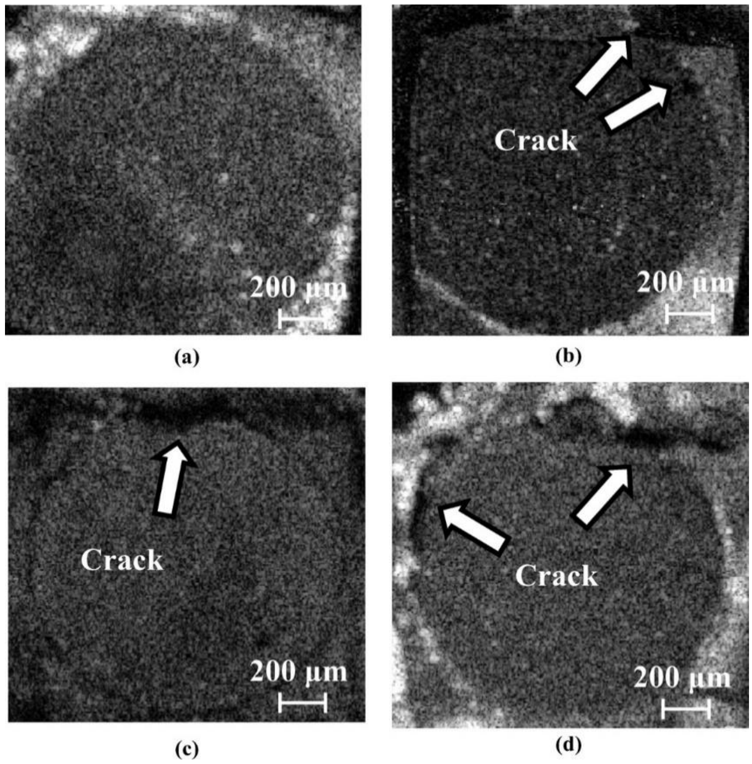

Figure 11. OCT images of ceramic/enamel interface under (**a**) an 80% load with 21 cycles, (**b**) an 80% load with 205 cycles, (**c**) a 70% load with 4071 cycles and (**d**) a 60% load with 38,271 cycles. Adapted with permission from Ref. [113] 2022, Elsevier.

Periodontal disease and dental caries are long-prevailing issues, and there is ongoing research concerning rapid, non-invasive diagnosis and treatment. In 2010, OCT was presented as a novel non-invasive approach to diagnose periodontal disease, with the aim of replacing clinical examinations or synergistically acting as a diagnosis aid [114]. PS-OCT in particular is useful for imaging caries and monitoring existing lesions on teeth. A common conventional technique for the detection of carries is radiography; however, the resolution of radiography is lower than that of OCT, and it only provides two-dimensional images [108]. Transversal microradiography, which has also been utilised in this application, has limitations in that it requires a thin sectioning process for imaging [115]. Exposure to radiation is an additional concern with the use of radiography in dentistry. Ultimately, compared to OCT, conventional methods do not provide the resolution, sensitivity and contrast required; therefore, early detection of lesions, periodontal disease and oral cancer can be difficult with conventional imaging techniques until they are well advanced, and remineralisation is not possible [108,115]. In PS-OCT, lesions appear with higher contrast, so they are easily seen. In addition, high-intensity specular reflection off lesions that usually prevent them from being detected is reduced with the use of PS-OCT. OCT may also be used to monitor the remineralisation of existing lesions, as well as the detection of secondary caries after dental restorations [115].

In addition to its high resolution, another attractive aspect of OCT in dentistry is the ability to obtain precise thickness and volume measurements. Wijesinghe et al. (2016) used the SD-OCT technique to produce a method to calculate the thickness and volume of remaining enamel regions during decay and demineralisation [116]. The study also successfully obtained high resolution images of ex vivo caries. OCT has also been applied in the detection of oral cancer. In 2004, Wilder-Smith et al. investigated the use of OCT for imaging and detecting epithelial changes and concluded that OCT has excellent potential for use as a diagnostic tool [117]. The same conclusion was reached in a 2005 study by Jung et al., who investigated the use of OCT for diagnosis of oral cancer in multiple stages of progression [118]. The results confirmed OCT to be a good potential diagnostic tool of oral cancer.

Tsai et al. also used the imaging the technique to scan various oral lesions and differentiate between them depending on their carcinogenesis stage [119]. After analysis of images, distinct features were identified that signified the stage of carcinogenesis. Mild and moderate dysplasia showed a significantly thicker epithelium compared to the control, but the boundary between the epithelium and the lamina propria was still visible. However, this boundary was no longer visible in the early-stage and well-developed squamous cell carcinoma samples. The significance and excellent potential of OCT as a diagnostic tool for oral cancer was successfully portrayed. Further development of OCT for oral cancer includes the use of surface plasmon gold nanoparticles to enhance contrast [120].

3.4. Lasers

Laser was first used in dentistry in the 1960s, and since then, applications have developed massively, rapidly allowing for greater efficiency, ease and comfort in treatments. Laser refers to light amplification by stimulated emission of radiation; concentrated, focused and coherent monochromatic radiation is emitted in single wavelength. When interacting with tissue, this radiation may be transmitted, absorbed, scattered or reflected depending on the optical properties of the tissue and the wavelength of the laser. Various effects may be achieved, including photoablation, photochemical effects, fluorescence and vaporisation. These can be utilised for a vast number of dental applications. Photoablation and vaporisation are used to remove tissue; fluorescence can be used to detect caries; and the photochemical effect may be used to initiate chemical reactions, such as curing of composite resin [121]. Lasers can be classified based on level of penetration, such as deep of superficial; wavelength; or application, such as soft tissue and hard tissue lasers.

3.4.1. Types of Lasers

The first lasers used in dentistry were neodymium-doped yttrium aluminium garnet (Nd:YAG) lasers, typically emitting a wavelength of 1.064 µm. In the first applications, the Nd:YAG laser was limited to a few soft tissue applications and was large and costly [122]. Carbon dioxide lasers, with a wavelength of 10.6 µm, were then introduced, which provided quicker healing times and allowed for haemostatic effects, as the diameter now exceed the average diameter of red blood cells (around 7 µm). CO_2 laser is absorbed easily by water and was therefore found to be very efficient on soft tissues [120].

The use of the erbium-doped yttrium aluminium garnet (Er:YAG) laser, with wavelength 2.94 µm, was an exciting development in dentistry, as it was one of the first lasers to work for both soft and hard tissue. Erbium can be absorbed by water in soft tissues and hard tissues but possesses less haemostatic ability than other options [85]. In addition, when water molecules in the tissue exposed to the laser absorb the energy and vaporise, they create bursts of gas to ablate the tissue, and this technique can be damaging to remaining healthy surfaces of teeth. Hence, in 2005, carbon dioxide lasers with a wavelength of 9.3 µm were introduced, which led to minimal thermal or mechanical damage while ablating hard tissues—enamel and dentin at high speeds [81,123]. Diode lasers may also be used in dentistry, and due to their excellent haemostatic ability, they are ideal for cutting through highly vascular soft tissues [85].

A summary of various lasers currently in use in dentistry and some of their popular applications is presented in Table 1 [82].

Table 1. Brief summary of commonly used lasers and their applications in dentistry. Adapted with permission from Ref. [82] 2022, IntechOpen.

Laser Type	Wavelength	Applications
CO_2	10.6 µm	• Soft tissue ablation • Treatment of lesions • Frenectomy and gingivectomy
Nd:YAG	1.064 µm	• Root canal therapy • Caries removal
Er:YAG	2.94 µm	• Caries removal • Root canal preparation
Er,Cr:YSGG	2.78 µm	• Caries removal • Cavity preparation • Bone ablation • Root canal preparation
Argon	572 nm	• Polymerization of restorative resin materials • Treatment of lesions • Frenectomy and gingivectomy
Diode	810–980 nm	• Promotion of healing of lesions or surgical wounds • Frenectomy and gingivectomy
HO:YAG	2.1 µm	• Treatment of lesions • Frenectomy and gingivectomy

3.4.2. Applications of Lasers

Laser can be used to remove damaged tissue and treat caries and carious lesions. In 2001, interactions of laser with hard tissues were investigated, and the study found that pulsed carbon dioxide lasers markedly inhibit the progression of caries and that the selective removal of carious tissue is possible with laser [83]. The same result was found by Rechmann et al. using a pulse 9.6 µm CO_2 laser in a short-term pilot clinical trial of 24 subjects [124]. Demineralisation was inhibited by 46% in 4 weeks and by 87% in 12 weeks.

A 2018 study by Chan et al. found a near-infrared imaging system combined with a 9.3 µm CO_2 laser aimed to ablate carious lesions in a selective manner. The laser, with the aid of an imaging, system successfully removed stimulated lesions and achieved a loss of only 12 µm of healthy enamel [125]. This level of precision achieved by a laser combined with a sophisticated imaging system could not have been achieved with a mechanical drill. This study is significant in highlighting how laser technology can continue to be developed in dentistry.

Aside from its reduced the precision, the use of a mechanical drill may also cause a build-up of matter on the tooth surface, which then reduces the adhesion of bonding agents. Phosphoric acid has been used to counteract this effect, but it causes further demineralisation of healthy tissue, whereas the use of laser leaves a clean surface [81].

In addition to removal of caries and inhibition of their progression, laser may also be applied as a preventative measure. Hossain et al. found that the use of a CO_2 laser enhances the resistance of enamel and dentin to caries formation [126]. This can be achieved if the tissue is exposed to laser to increase its temperature without ablating it. The result is a crystallographic change that causes a denser and more acid-resistant surface [81].

The haemostatic abilities of laser make it a very useful and versatile tool in dentistry. Some lasers may be employed to promote healing after tooth extraction. Lasers are able to produce micro-holes at the site in order to increase blood flow and increase the attachment of osteoblasts to the implant, thereby increasing the success rate of dental implants and simultaneously lowering the risk of infection [81]. Hamad, Naif and Abdullah investigated the use of a diode laser in the healing of extracted tooth sockets of rabbits. Histological examination showed that the use of laser formed new bone faster, with increased density and volume compared to control sockets [127].

Further benefits of laser include its microbial inhibition capability, which make it ideal for treatment of infections.

3.4.3. Peri-Implantitis

Peri-implant infections can be difficult to treat because of contamination of the implant surface and adjacent tissues. Romanos and Nentwig found that a CO_2 laser can be used to decontaminate and treat peri-implantitis [128]. In 2015, Aoki et al. confirmed laser treatment is important in the treatment of periodontal and peri-implant infections [129].

Numerous other studies investigated the effects of LASER therapy on implant surfaces [130]. In a 2008 in vitro study, Lee et al. utilized CO_2 and Er,Cr:YSGG lasers to evaluate cellular response on cells similar to osteoblasts when planted on titanium discs. The results demonstrated a significant effect on the proliferation rate of the discs irradiated with either one of the two lasers [131]. Er:YAG lasers offer promising results for the treatment of peri-implantitis. Er:YAG laser has the potential to remove plaque and calculus from the abutments of implants without damaging the surface [132]. Studies evaluated the effects of lasers and compared them with conventional curette groups. The erbium laser showed promising results for the debridement and removal of granulation tissues; moreover, histological results revealed desirable bone formation and a greater contact between the implant and bone of the laser-treated group [120].

The literature suggests the beneficial effects of CO_2 lasers for the treatment of peri-implant defects when used in conjunction with collagen membranes or other bone-grafting materials [128].

3.4.4. Regenerative Laser Periodontal Therapy

Regenerative periodontal procedures, demonstrating remarkable alveolar bone growth, revealed a layer of epithelium instead of cementum along the surface of the root. Histological examination revealed that an essential parameter to promote healing is the need to form a junctional epithelium with CTA (connective tissue attachment) [133,134]. Removal of crestal epithelium inhibits the movement of crestal cells into the pocket [135,136]. This forms the foundation for regeneration, which is then initiated when new fibres are introduced to the root surface. The frameworks of other treatment modalities, such as the modified Widman flap procedure, subgingival curettage and the “excisional new attachment procedure”, rely on the exclusion of pocket epithelia and the subsequent creation of an environment for the formation of new CTA [120].

The distinctive features of laser in periodontal therapy can be utilized for epithelial removal. A carbon dioxide laser (10.6 µm wavelength) has the ability to delay epithelialization in wounds. Studies have demonstrated the potential of CO_2 laser to delay epithelial growth for 14 days following a periodontal surgery. CO_2 laser can therefore be utilized to eliminate the epithelium without resulting in any damage to the underlying connective tissue layer [137]. For a detailed conceptualization of laser light for the epithelial retardation procedure, it is essential to understand the mechanism of wound healing. Pulsed CO_2 has the potential to form a distinctive wound in the gingiva. This is a unique vaporization mechanism of intracellular fluid that subsequently results in degradation of cell structure [138]. Laser wounding results in retardation of re-epithelialization due to parameters such as diminished wound contraction and reduced inflammatory response. Figure 12 illustrates a few advantages for the use of lasers in periodontal therapy in contrast to conventional periodontal surgeries [120].

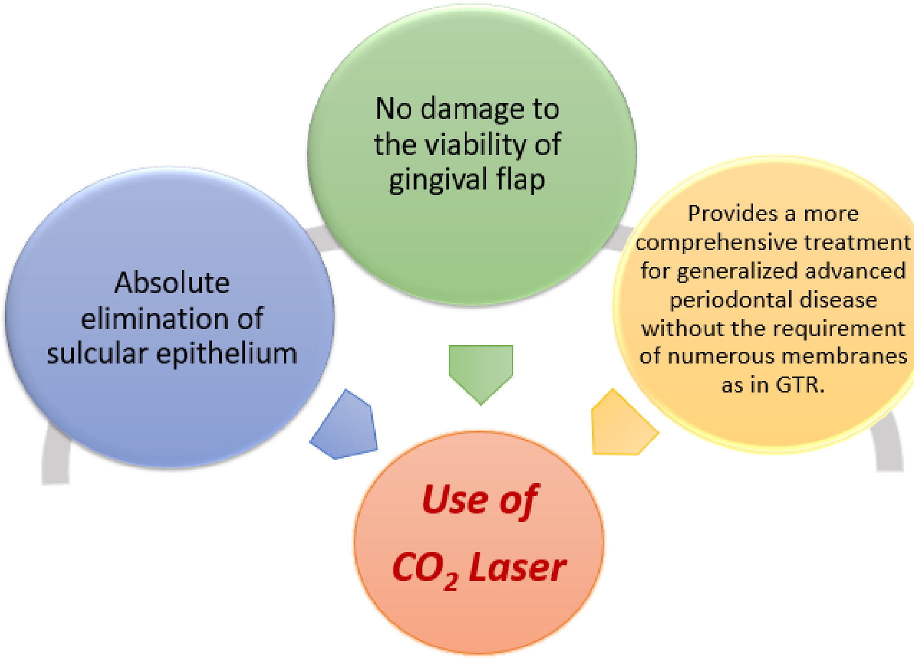

Figure 12. Advantages of laser in periodontal therapy in contrast to conventional periodontal surgeries.

A brief summary of uses of laser in dentistry is presented in Table 2; the applications are vast for both soft tissue and hard dental tissue. Other hard tissue applications include bleaching for cosmetic purposes, diagnostics, treatment of hypersensitivity, and restorative removal and curing. Additional soft tissue applications include photodynamic therapy for malignancies, gingivectomy (removal of hyperplastic tissue), frenectomy, crown lengthening and periodontics [85]. The reader is directed to a review of laser for restorative dentistry by Najeeb et al. for further reading on the applications of lasers within dentistry.

Table 2. Summary of advantages of laser therapy in dentistry compared to conventional therapies.

Summary of Advantages of Laser Therapy in Dentistry Compared to Conventional Therapies
Reduced need of anaesthesia
Reduces pain with analgesic effects
Haemostatic effects; reduces bleeding and tissue inflammation
Very precise cutting; minimises damage to healthy tissues
Ability to ablate and vaporise dental hard tissues
No issue of painful vibrations caused by conventional equipment, such as dental drills
Microbial and bacterial inhibition
Improved cell metabolism and biostimulation
Patients with higher sensitivity can be treated with photomodulation therapy

3.5. Photodynamic Therapy

3.5.1. Management of Symptomatic Oral Lichen Planus

Lichen Planus is a chronic inflammatory disease clinically classified as reticular lesions, which are generally asymptomatic, whereas its erosive and atropic forms, presented as white lines (Wickham's striae), are painful and require immediate medical attention, as they have the potential to undergo a malignant transformation [139]. Corticosteroids, invasive surgical procedures and laser therapy are the therapeutical procedures used, each of which have their own adverse effects, including mucosal atrophy, candidiasis, GIT disorders and adrenal insufficiency [140]. Therefore, photodynamic therapy is highly recommended as an alternative treatment plan.

Figure 13 illustrates the mechanism of action of PDT. The molecules of photosensitizer are activated by the laser light and are converted into an excited triplet state, which then reacts with oxygen molecules to form reactive oxygen species. These reactive oxygen species have the potential to kill the target cells and therefore have tissue-healing and regenerative properties [141,142]. Various studies were conducted to investigate the efficacy of PDT in contrast to corticosteroids. A systemic review by Akram et al. confirmed the effectivity of PDT for the management of oral lichen planus; however, further research fortified on standardized parameters of PDT, such as fibre diameter and lesion size, is essential [120].

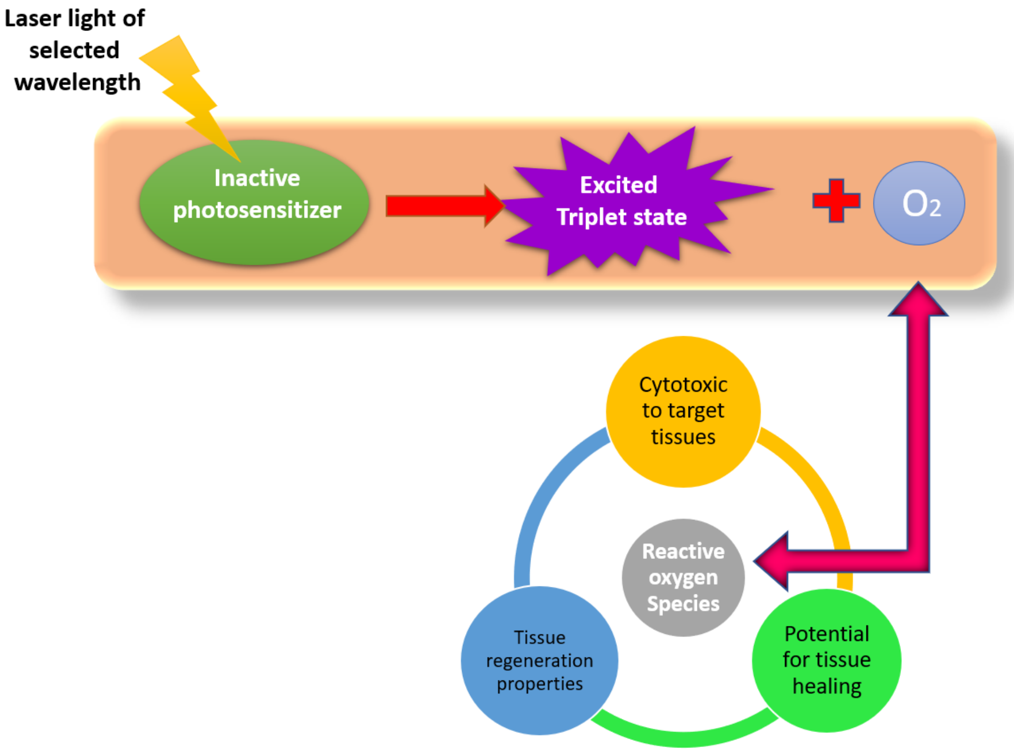

Figure 13. Mechanism of action of PDT against OLP.

3.5.2. Management of Chronic Periodontitis in Smokers

Chronic periodontitis is a disease of bacterial origin that proceeds to gradual soft tissue and bone destruction, thereby forming a periodontal pocket, along with the gingival recession [103]. The literature suggests smoking as one of the highest-risk factors associated with disease progression. Moreover, smoking is also accountable for depriving normal flora of the oral cavity in healthy individuals; therefore, mechanical debridement of subgingival calculus is not favourably managed [143–145]. Evidence suggests management by PDT has the potential to swiftly repress the target cells (microbial species) with the same mechanism of action as illustrated in Figure 13. However, there is a dearth of literature, and further randomized clinical studies are highly recommended to evaluate the efficacy of PDT in contrast to scaling and root planning for a gain in the level of clinical attachment [146].

3.5.3. Anticancer Therapy

Evidence reports oral squamous cell carcinoma as the eighth most common cancer globally [147]. Despite recent advancements in treatment regimens, such as chemotherapies or radiotherapies, the fatality rate has not significantly decreased, and adverse effects of such treatments, including severe jaw pain, salivary gland disorders and chewing problems, are too common to be neglected [148]. PDT-based management of malignant lesions aims to provide a less invasive soft tissue preservation treatment, as photosensitizers have the ability to target tumours rather than the surrounding soft tissues [149]. Foscan®-based management, which has been approved by the EU, aims to destroy the local tumour and significantly preserve the functions of the surrounding organs [122]. Other common photosensitizers include Photofrin® and ALA [122,150]. So far, these photosensitizers have been used for the management of head and neck carcinomas in around 1300 patients [142].

3.6. Quantum Dots

Quantum dots are semiconductor nanocrystals with unique optoelectronic properties; when stimulated and excited, they release energy via single photons. The wavelength of the light emitted is dependent on the size, composition and shape, something which can be easily changed to produce a specific desired wavelength. As the size decreases, the wavelength emitted decreases, and hence, the photoluminescence colour tends towards the blue end of the spectrum. As the size increases, the wavelength emitted increases. The diagram below represents the applications of quantum dots in biomedical and biological application [151].

The potential applications for quantum dots in both medical and non-medical fields are various, including fluorescent labels for biomedical imaging and cancer research, photonic devices, sensor materials, quantum communication networks, greater efficiency in LEDs and solar cells, quantum computing, drug delivery and engineered tissues [152]. Nanotechnology is expected to revolutionise science and technology, and dentistry is no exception to this. Improving understanding to a nanometre resolution allows for the development of novel dental materials, techniques and tools. A good example of this is how research on micro and nano-leakages of resin-based dental restorations has allowed dentists to work towards preventing secondary caries, as referred in Section 3.3.

One application of quantum dots is the development of cosmetic dentistry. Natural teeth emit light at 440 nanometres when exposed to ultraviolet light and in daylight. In order for resin composites to closely resemble the colour and transparency of natural teeth, the optical properties of the resin composites must be considered, and emission under UV must occur at a similar wavelength. However, restorative materials tend to have very different luminescent characteristics, as discovered by Wozniak and Moore [152]. Luminophores inserted into dental resin can be used to alter optical properties, but the result still does not resemble natural teeth [73]. Alves et al. investigated the use of core-shell quantum dots to alter the florescence and optical properties of dental resin composites. The authors proved that the incorporation of core-shell nano-structured CdSe/ZnS quantum dots into dental resins allows tailoring of fluorescence intensity to more closely resemble natural human teeth [73].

The use of nanoparticles within adhesive resins causes clumping and agglomeration, making it structurally weak. Garcia et al. proposed the synthesis of zinc oxide quantum dots (ZnO) to an adhesive resin due to their non-agglomerated nature [153]. The findings suggested that this was a possible and reliable method to overcome the agglomeration concern associated with nanoparticles within fillers. The fluorescence properties of quantum dots were applied in vitro and in vivo by Chalmers et al. to label bacterial cells [154]. This method was then compared to the conventional way of marking bacterial cells using fluorophores, and the use of quantum dots was shown to be more advantageous in achieving single-cell resolution with a standard epifluorescence microscope. This is significant because gaining insight into the interactions between various bacterial species allows for greater understanding of the development of biofilm.

Applications of quantum dots in oral cancer research are also of particular interest, as they may be combined with antibodies to bind to specific proteins of tumour cells, thus acting as fluorescent markers for sensitive detection [155,156].

3.7. Photoacoustic Imaging

In the early 1880s, the photoacoustic effect was discovered in numerous studies that finding that when some material are illuminated by modulated light, they can emit sound waves. Following this discovery, Hordvik and Schlossberg applied the photoacoustic technique as a non-invasive imaging method to measure the absorption coefficient in solid samples with high sensitivity [157]. This technique is carried out by a combination of visible and near-infrared excitation with acoustic detection [158]. In dentistry, photoacoustic techniques have been used for diagnosis of caries, periodontology, dental implants and blood detection in dental pulp [157]. As shown in Figure 14, this system includes a Q-switched Nd:YAG laser (as an incident pulsed light beam source), which is elevated the beam to a certain height using a right-angle prism and multiple mirror assemblies. A part of this beam is divided with a beam splitter and fed to a photodetector, whereas the other part is reflected downwards with a controlled mirror [157]. This precise method is highly reproducible; the amount of the photoacoustic signal is directly related to the light absorbed by the tissue [159]. Such an imaging method can be performed at visible or infrared wavelengths (532 and 1064 nm), but for deep-tissue imaging, a near-infrared wavelength is recommended. Therefore, this technique could be beneficial in dental applications to detect carious lesions in the early stages [157].

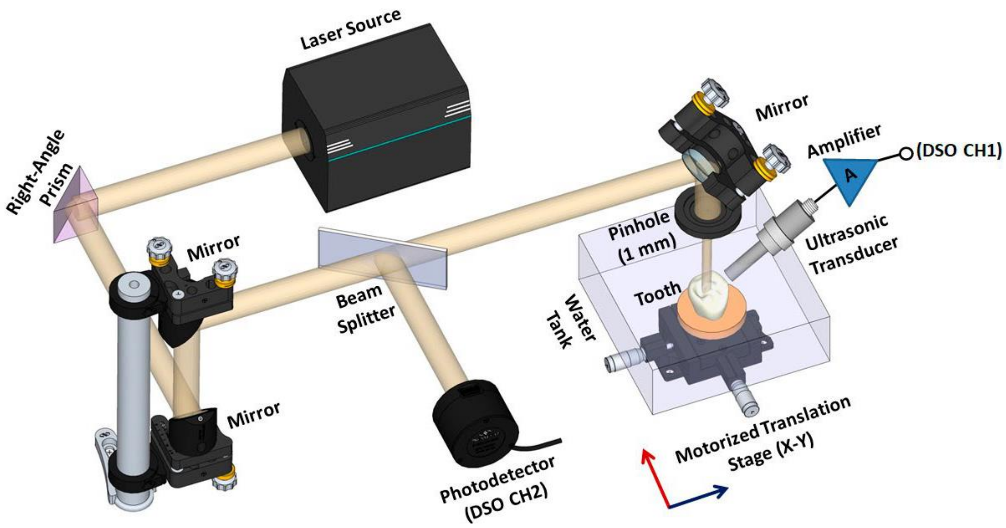

Figure 14. Simple diagram of photoacoustic imaging system. Adapted with permission from Ref. [157] 2022, PMC.

3.8. Photothermal Imaging

In recent decades, photothermal imaging has been developed as a non-ionizing method for dental imaging to detect caries. With technique, temperature variation of the subject is measured without contact; therefore, it can detect early caries with better sensitivity [160]. The thermography instrument (Figure 15) includes a heat source; a single detector, such as an IR camera, which monitors surface temperature; a signal generator; and a computer for synchronizing systems to perform signal processing and to reconstruct algorithms. This method is very suitable for imaging biological tissue because thermal-waves do not have resolution and depth limitation of optical or ultrasound waves [161].

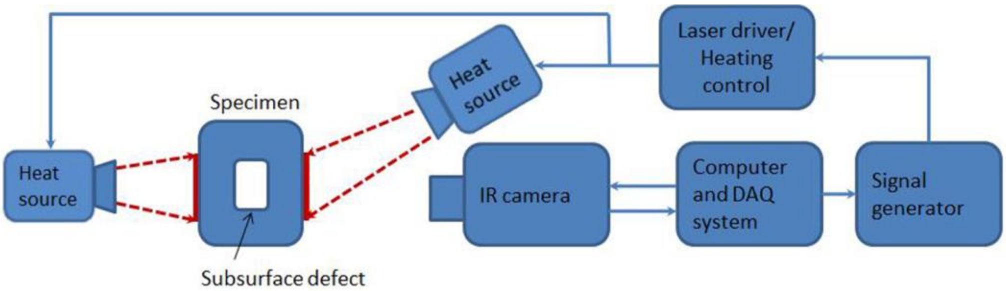

Figure 15. Schematic of active thermography system. Adapted with permission from Ref. [161] 2022, AIP Publishing.

3.9. Photobiomodulation (PBM) and Ozone Treatment

Another clinical application of biophotonics in dentistry is the use of photobiomodulation (PBM) and ozone treatment. For instance, one interesting study investigated management of periodontal disease with adjunctive therapy with ozone and photobiomodulation. In this study, both ozone and PBM appeared to be effective adjuvant treatments to scaling and root planning (SRP), obtaining a slightly better outcome for the latter in the long term, with significant differences at T5 and T6 for probing pocket depth (PPD) [162].

4. Conclusions

In this review paper, we comprehensively discussed the application of biophotonics in dentistry, especially elements such as photoelasticity, interferometry techniques, optical coherence tomography, laser and quantum dots. The development of photonics has been invaluable in many dentistry applications, including but not limited to diagnostics, biomechanical studies, treatment of oral cancers and caries and the development of dental prostheses. Photoelasticity is an optical technique that has been applied for many years in experimental stress analysis. Most transparent materials exhibit a temporary birefringence property when exposed to strain and loading due to changes in molecular orientation distribution. ESPI is a non-destructive optical technique and is capable of obtaining measurements of the surface with high sensitivity in a non-contact manner. Other uses of ESPI include the study of dentin compression in water, whereby the Young's modulus of root dentin under compression can be easily detected.

Moiré interferometry is an alternative optical method for strain analysis, with applications in many fields, including biomechanics, fracture mechanics and the study of composite materials. The high sensitivity associated with moiré interferometry makes it a valuable technique for the real-time study of the biomechanics of dental structures. Optical coherence tomography (OCT) is a non-invasive, non-destructive, high-resolution, cross-sectional imaging technique widely used in various clinical applications, including ophthalmology, dentistry and gastroenterology.

Laser refers to light amplification by stimulated emission of radiation; concentrated, focused and coherent monochromatic radiation is emitted in a single wavelength. When interacting with tissue, this radiation may be transmitted, absorbed, scattered or reflected, depending on the optical properties of the tissue and the wavelength of the laser. Various effects can be achieved, including photoablation, photochemical effect, fluorescence and vaporisation. Photoablation and vaporisation are used to remove tissue, fluorescence can be used to detect caries and the photochemical effect can be used to initiate chemical reactions, such as curing of composite resin.

Quantum dots are semiconductor nanocrystals with unique optoelectronic properties; when stimulated and excited, they release energy via single photons. The potential applications for quantum dots in both medical and non-medical fields are considerable, including fluorescent labels for biomedical imaging and cancer research, photonic devices, sensor materials, quantum communication networks, greater efficiency in LEDs and solar cells, quantum computing, drug delivery and engineered tissues. Additionally, other dental applications of laser could be beneficial in oral surgery, prosthodontics, endodontics and orthodontics. For instance, applications in endodontics could include smile design, caries removal, cement curing and tooth etching, among others. For orthodontics, applications could include bracket curing, removal of residual cement, post orthodontics and exposure of impacted teeth. Finally, the best examples of prosthodontics applications are crown contouring and lengthening and sulcus deepening.

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