Optical Coherence Tomography in Dentistry

Optical Coherence Tomography (OCT), a method to "see inside of things" without destroying them, has been applied to subjects ranging from materials science to medicine. This book focuses on the biomedical application of OCT in dentistry, covering topics from dental materials to clinical practice.

Since the introduction of the OCT method in ophthalmology in 1991, and then dentistry in 1998, developments in OCT methods, particularly in biomedical areas, have led to its dissemination worldwide. The chapters of this book cover the basics and recent global advances of OCT in dentistry, including an overview of the method and its use in cariology, restorative dentistry, dental materials, endodontics, pediatric dentistry, orthodontics, prosthodontics, soft oral tissues and nanodentistry.

This book will be of interest to both newcomers in the field as well as those already working in OCT, either in research and/or the clinic. It will be of great use in courses on optical imaging applied to biomedical areas, particularly where it can provide real-life examples of the application of OCT.

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Scientific Developments to Clinical Applications

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Preface

Optical coherence tomography was born to see inside the eye, and it is has evolved to be "the eye seeing" throughout most parts of the human body. OCT, as it is commonly known, is one of the most fast growing optical imaging techniques, which provides real-time images capable of submicron resolution with penetration depths up to few millimeters. It can be used not only in hard and soft tissues, but has also been widely exploited on materials evaluation, including biomaterials.

The motivation to this book arose from the fast growing OCT applications in dentistry, which is opening new opportunities for early, noninvasive diagnostics or treatment follow-up for oral diseases. This will hopefully complement the state-of-the-art literature on OCT applications in life sciences, which is presently available.

The book is designed for professionals working in clinical practice, undergraduate, graduate students and post-docs performing research in this field, as well as industry professionals who are on the frontiers of optical based instrumentation for health diagnostics. It has been written to be used at all levels, with background chapters as well as updated bibliography on all areas of dental OCT. It can also be used in courses such as optical imaging techniques, lasers in dentistry, photobiomodulation, among others. Professional societies, such as SPIE and OPTICA, who provides annual short courses on biophotonics, will certainly benefit from this book. The core physical background will be present in one chapter but this will not be required for comprehension of the other more applied and practical chapters.

The chapters are organized in three main parts: two chapters are devoted to the principles of optical imaging, and the basics of OCT, both from a nontechnical and technical perspective and its early applications to dental science.

Ten chapters are devoted to OCT applications in specific areas of dentistry, from cariology and dental materials to the recent research field of nanodentistry.

Then, it ends with a chapter on what can be expected for developments in dental OCT. Each chapter will highlight the basic anatomy or features of the studied subject, then the conventional methods of diagnosis or analysis – in the case of materials – and then the literature results on the subject, with insights by the authors own research. Where applicable, clinical developments will be highlighted. The sequence follows the way that, in general, undergraduate syllabus courses are given.

We hope you have an enjoyable read!

Anderson S. L. Gomes
Denise M. Zezell
Cláudia C. B. O. Mota
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1

Overview of Optical Imaging Methods Used in Dentistry

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1.1 Introduction

The first action of any dentist is to ask the patient to open their mouth so that they can undertake a visual inspection of the exposed surfaces of the tooth. Optical imaging, using the clinician's eyes as the detector, is still, therefore, the most important diagnostic tool employed. As well as looking at the tooth

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surface, the skilled practitioner will also move their head around using the way that the light is returned from the tooth to make clinical judgments on the status of the teeth being observed. They are unlikely to consider deeply the way that the electromagnetic radiation, light, is interreacting with the molecular and crystal structure of the tooth, but it is this interaction that they are observing, and crucially how this interaction changes when there are local changes in the tooth. The aim of the instrument developer is therefore to provide the clinician with information that they cannot see directly with their eyes to enhance their decision making. This extra information may be to provide details on the internal structure of the tissue through to microscopic changes that are taking place dynamically on the surface of the tooth. In order to deliver these extra clinical insights different wavelengths (colors) of light may be used or methods that help to separate out the surface reflections from light scattered back from greater depths. Crucially though this information needs to be taken with minimal perturbation to the tooth, rapidly and a frequently over looked complication, with a live patient present in the dentist's chair.

Before considering the physical details of such interactions and instrumentation it is important to consider what the dentist actually wants. In relation to hard tissue, ideally, they would like to be able to detect, and quantify, early caries lesions assessing the level, and rate, of mineral loss from the tooth. These measurements should be rapid and provide information on not just the surface interactions but also what is taking place at deeper levels within the tooth. The method should clearly be non-invasive and "patient friendly" but present no risk to the subject such as that in the case of ionizing radiation (X-rays). Implicit in these comments is the requirement to detect problems early when the treatment will be as minimally invasive as possible, ideally using re-mineralization of the tooth to heal early lesions. A further practical consideration is that the method should be cost effective, and relatively fast providing real-time information to the clinician and patient. There is little point in taking several minutes to image each tooth with very high resolution as this would increase patient "chair time" making the method impractical in a real clinical setting. If the method is ever going to reach the clinic it will also need to be commercialized meaning it must be easy to operate, reliable and fit within the cost structure of the dental practice.

As well as the detection of early caries, a focus throughout this book, instruments are also required to assess the status of the gum and softer tissue – a growing area of concern as fluoride toothpastes improve the general status of dentition around the world. Here the requirement may be less of obtaining images but providing indications of levels of infection and blood flow through the tissue as a guide towards the vitality of the tissue. There are also requirements for methods that might be used during more invasive treatments to ensure that the correct level of diseased tissue has been removed and thus minimizing the risk of re-infection and further, even more invasive, treatment.

Before considering more details of practical physics and optics behind the various methods to be discussed, it is worth taking a moment to think about the difference between detecting, diagnosing and treating a condition. Although the terms are often, incorrectly, used interchangeably some thought should be given here for any long-term practical devices that may be dreamt up. In basic terms, detection is the identification of a problem, diagnosis is then the quantification of the problem and the initial consideration of a treatment plan, and then one moves onto the treatment phase, which is then the implementation of the diagnosis clinical pathway. In the case of the dental surgery, it is possible that these tasks may be undertaken by different people from dental nurses, dental hygienists through to dental surgeons. Each will have subtly different requirements and thus, in the long term, a suite of imaging methods may be required to deliver the best possible solution to each specialty. In all research work it is always worthwhile to keep these considerations in mind as it can help to increase the longer-term impact of any practical research.

The chapter will now go on to provide the basics on the physics of light and the way that it interacts with tissue. This understanding will then be used to show such interactions can help provide information that cannot just be seen with the dentist's eyes alone, explaining how several of the most recent optical methods, applied to dentistry, operate (Hall et al. 2004). All of this will, as far as possible, be set in the context of how such instrumentation can help the clinician improve patient care, which in the long term must be the aim of all such instrumentation.

1.2 Basic Properties of Light

At the heart of all the methods described in this book is light as a source of energy. It is then subtle changes in the properties, or quantity, of the light that is then seen by the detector that is then related back to the status of the sample. As a source of energy, light is part of the electromagnetic spectrum, but crucially in the region in which our eyes operate as a detector. This visible portion of the spectrum extends from around 400 to 700 nm (violet to deep red). At shorter wavelengths one enters into the region of UV excitation and longer than 700 nm is in the near infrared region. The wavelength of the light plays a very important role in the way that it interacts with the tissue. The exact nature of light has also been a subject of controversy since the 16th century, is light a wave (classical physics) or a particle (quantum mechanics or Newton's "Corpuscles")? Numerous experiments have been undertaken over the intervening 400 years and the conclusion is the light can exist in both "forms". Throughout this chapter, and indeed the entire book, explanations

of the interaction of light with tissue will be given using both waves and particles. Generally, the one that provides the clearest explanation of a particular phenomenon will be used.

As a wave light obeys the equation $c = \nu\lambda$, where ν is the frequency of the light, λ is the wavelength and c the speed of light in a vacuum (defined in 1983 as being 299, 792, 458 ms^{-1}). The other fundamental equation related to light is the energy present for an individual photon (particle of light). In Planck's equation $E = h\nu$ where E is the energy of an individual photon, h is Planck's constant (6.63×10^{-34} Js) and ν again the frequency of the light. As a wave light has (a) wavelength: the distance from one peak (or trough) on the wave to the next one, and (b) frequency: the number of waves passing a point in a second. The height of the wave is known as the amplitude. These are illustrated in Figure 1.1.

As mentioned above the speed of light, in a vacuum, is now defined and according to Einstein nothing can travel faster than this velocity. However, when light passes through a material it is slowed down and the ratio of the velocity of light in a vacuum to its velocity in a material is known as the material's refractive index "n". For water this value is around 1.33, for glass 1.5 (or a velocity of around 2×10^8 ms^{-1}) but for dental enamel it is as high as 1.62. The exact value of the refractive index depends on the wavelength and thus different wavelengths of light will be slowed to greater or lesser extent. Generally, the longer the wavelength of light, the less the light is slowed. The high refractive index of dental enamel leads to the light being guided through the tooth as explained later.

The final property of light we need to consider is that of polarization. Polarization is the property of the direction of the wave's oscillation. For a

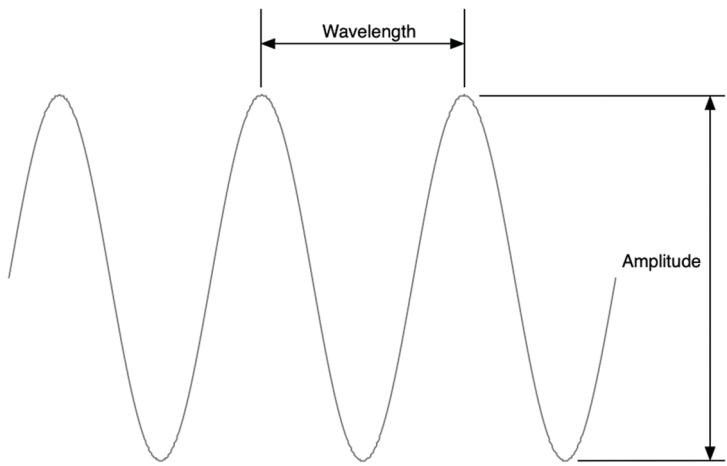

FIGURE 1.1
Diagrammatic representation of a light wave.

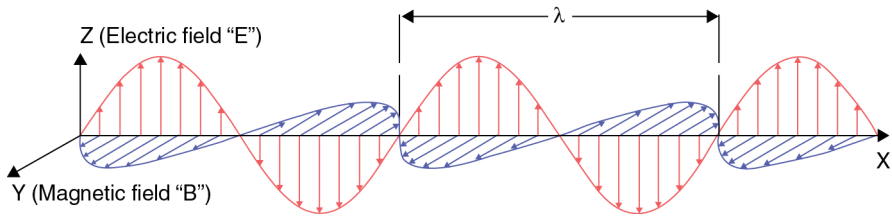

FIGURE 1.2
Representation of a wave illustrating the property of polarization.

wave traveling in the *x* direction, the waves can either oscillate in the *y* or *z* directions, or a mixture of the two. In the case of light, which is a combination of oscillating electric and magnetic fields, it is the direction of the electric fields' oscillations, which defines the direction of polarization. In Figure 1.2 the light is vertically polarized. A beam is *linearly polarized* if all of the waves are oscillating in the same direction, and *un-polarized*, or *randomly polarized*, light is a combination of waves oscillating in all directions. Light that is un-polarized can be separated into two polarization states (vertical and horizontal) using several components including specially coated optics, certain crystals and a specific polarization selected using special plastics (such as that used in sunglasses).

1.3 Interaction of Light, Matter and Tissue

Having described the basic properties of light we now need to consider how these properties are affected by interactions with materials, including both soft and hard tissue. In any optical detection system it is changes in the properties of light that produce the contrast in the data, or images, that can then be related back to clinical problems. All of the interactions of light are illustrated in Figure 1.3.

1.3.1 Reflection

Reflection occurs when light hits a surface and is then directly "thrown back" off the surface at a well-defined angle. Indeed the angle of the incoming light, relative to a line drawn normally to the surface, is equal to the outgoing angle, the other side of the normal as illustrated in Figure 1.3(a). Apart from the change in direction of the light there is no other alteration to its properties. In particular, the wavelength and polarization are not affected. The fact that the polarization is not affected can be used to remove surface reflections if a polarized light beam is incident on a reflective surface. Using a polarizing

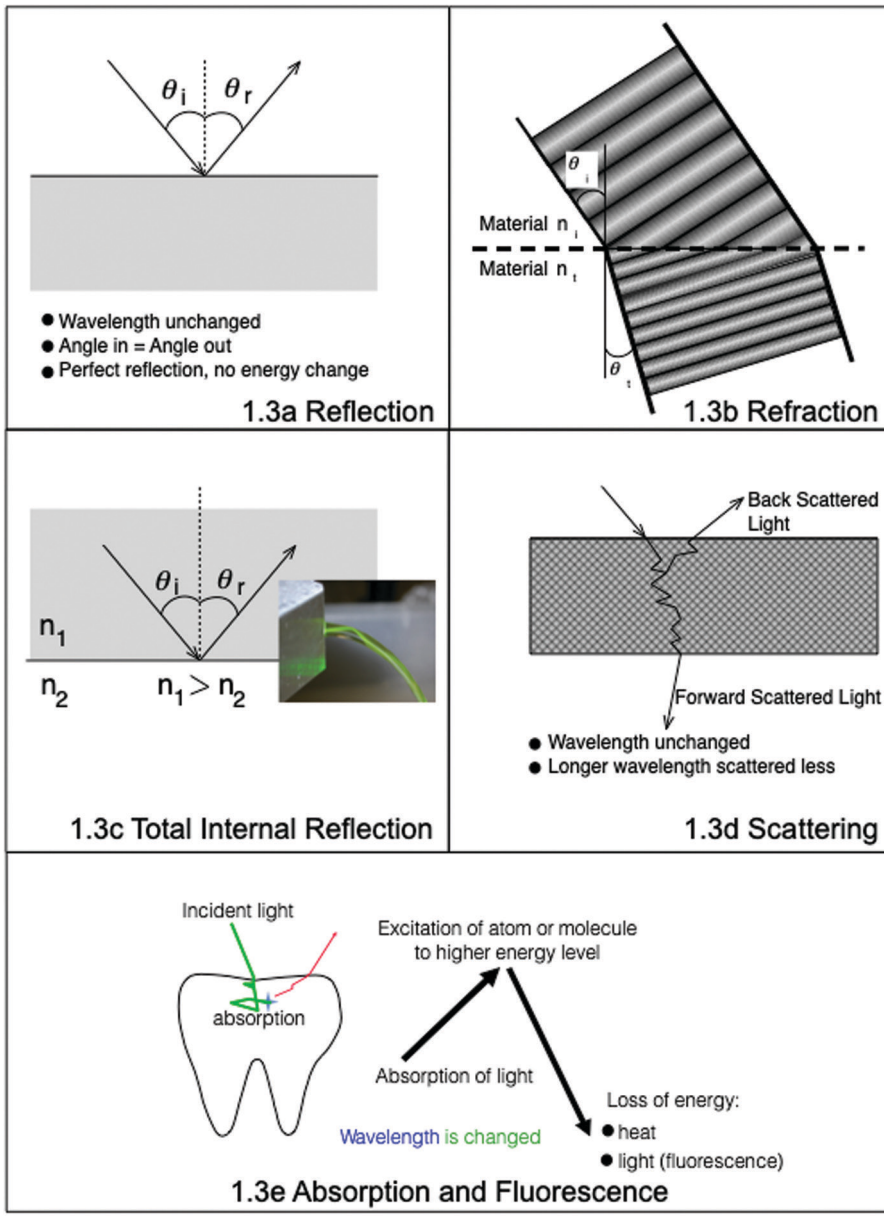

FIGURE 1.3
Interactions of light with matter. (a) Reflection. (b) Refraction. (c) Total internal reflection (inset shows TIR in a water flow). (d) Scattering. (e) Absorption and fluorescence.

filter, which is at ninety degrees (crossed) with the incoming polarization of light the reflected light will be rejected. This is a method frequently used in optical coherence tomography (OCT) systems to remove the surface reflections.

The most common reflective materials are metals and thin coatings of aluminum and silver are frequently used to coat glass surfaces to produce mirrors. Gold is also highly reflective but due to its atomic structure certain wavelengths are transmitted and hence the reflected light has a gold rather than white color. However, all surfaces that are not highly absorbing do reflect a certain quantity of incoming light unless they are specially coated. This reflection is due to their refractive index and is known as Fresnel reflection. If light hits glass at normal incidence then 4% of the light will be reflected from the surface, with this percentage increasing as the angle of incidence increases. This effect can be seen in the type of mirror used in the home when one sometimes sees a double image, with a strong reflection off the back silver-coated surface and weaker almost "ghost" image from the reflection from the front of the glass. Although Fresnel reflection does not change the polarization of the incoming light one polarization is preferentially reflected and again this effect can be used in certain optical instruments. This preferential reflection is the reason that polarized sunglasses enable you to see more clearly through water on a sunny day. The light reflected off the surface is partially polarized and by using sunglasses, which reject this polarization, one removes the reflected light.

1.3.2 Refraction

Refraction of light is due to a material's refractive index, which causes a light beam to "bend" as it moves from one material to another. Figure 1.3(b) illustrates the reason for this. If one considers a plane wave of light reaching a transparent material where the refractive index is higher, the first part of the light will enter the material but will be slowed down. This means that light that has not yet entered the material and will start to "catch up" with the part of the wave already inside. This means that the wave will appear to pivot, or bend, towards the normal of the surface. On exiting the block, the light will travel in the opposite manner such that when the wave fully emerges it will be parallel with the input beam. The level of bending depends on the relative refractive indices between the two materials and is given by Snell's law:

$$\frac{\sin\theta_i}{\sin\theta_t} = \frac{n_1}{n_2} \tag{1.1}$$

As mentioned earlier the refractive index of a material varies with the wavelength of the light so although the actual wavelength and properties of the light are unchanged, white light can be spread spectrally into its component colors due to the refractive index of a material. This is how a prism produces a "rainbow" from white light. Thus refraction only changes the direction of the light, and also the time that light may take to traverse a particular distance (as the light may be traveling more slowly).

1.3.3 Total Internal Reflection

The refractive index of a material also leads to two particular effects within dental tissue. The first is known as total internal reflection and plays an important role in the way that light is guided through a tooth. The effect can be predicted from Snell's law. For a fixed pair of refractive indices, there will be a point where the sine of the angle of the transmitted beam will become greater than 1, which is not possible (Figure 1.3(c)). The point at which this value becomes 1 is known as the critical angle and is given by

$$\theta_c = \arcsin\left(\frac{n_2}{n_1}\right) \tag{1.2}$$

For glass with a refractive index of 1 and where air ($n_2 = 1.00$) is the second medium the critical angle is 41.8°. If light hits the interface at an angle greater than this then it will be reflected rather than transmitted. This effect is illustrated in the inset in Figure 1.3(c) where a laser is being guided down a water flow (in air) due to total internal reflection. This is also the way in which optical fibers work and in teeth the enamel rods, or prisms, guide light in exactly the same way. In fact, the dimensions of an enamel rod are very similar to those of a single mode optical fiber, though the refractive index is higher in the case of enamel. This has the effect of helping to guide the light through the tooth towards the dentine where the light is scattered. There is in fact some guiding within the dentinal tubules but this is due to multiple scattering (Kienle et al. 2006). As will be described later, these two effects are the cause of early lesions appearing to the eye as a "white spot".

1.3.4 Scattering Including Raman Scattering

Scattering occurs due to differences in the local refractive index of the sample and is illustrated in Figure 1.3(d). The level of scattering depends on (a) the local difference in refractive index; (b) the size of the particle or feature; thewavelength of the light. In a scattering process there is no change of c)) wavelength with the exception of Raman scattering, which is discussed later. ,Light at longer wavelengths is scattered less than shorter wavelength

which is one of the reasons near-infrared light is used for imaging in OCT as it penetrates as a well-structured beam further into the tissue.

The exact way (level of scattering and angular range of scattering) that light scatters depends on the relative size of the particle to the wavelength of light, and different scattering regimes use different approximations to solve the complex mathematical equations, which describe the process. At a larger scale scattering can be considered as being probabilistic and a value assigned to the chance of a photon being scattered over a particular angular range.

It should also be noted that the level of scattering is affected by the polarization of the light entering the sample relative to the orientation of the feature causing the scattering, and scattered light does have its polarization changed. Thus, through an examination of the polarization angle of the light, further contrast enhancements are possible to separate out highly scattered from less strongly scattered light and even reflections.

In general, the scattering processes do not change the wavelength of the light being scattered; the exception to this is in certain materials, which are described as being Raman active. The first observation of inelastic light scattering (change of wavelength) was made in 1928 by C.V. Raman and K.S. Krishnan and led to the award of the Nobel Prize in physics in 1930. Sir Chandrasekhara Venkata Raman, an Indian, was the first Asian and non-white person to receive a scientific Nobel Prize and the effect was rapidly named after him. As only around one photon in 10 million is Raman scattered (Raman scattering probability ~ 1×10^{-7}) the technology at the time was not sensitive enough for widespread practical application of the method. Instead near-infrared spectroscopy became the standard analytical tool used to help determine molecular composition. The laser and more recently charge-coupled device detectors have radically transformed this position.

The Raman effect can be explained both using a photon or electromagnetic wave approach. In the latter, the electric field of the light wave deforms the electric field of the molecule, causing the latter to oscillate at the same frequency as the light wave. The molecular oscillating field then acts as a dipole oscillator emitting light at the same frequency as the light field (conventional scattering) when there are no Raman active vibrational modes. An alternative, is that when the molecule is Raman active, part of the electromagnetic wave is used to excite a vibrational mode in the molecule and the resulting molecular dipole oscillates at a lower frequency, emitting light at a slightly longer wavelength than the incoming light. This emitted Raman light is known as the Stokes wavelength as it emerges at a longer wavelength. If the molecule is already in a more energetic state that when the light is re-emitted it may have gained energy leading to a shorter emission wavelength and anti-Stokes scattering, which has an even lower probability of occurring.

The Raman effect can also be considered, and perhaps more easily appreciated, using a quantum mechanical approach. The incoming photon

excites the sample into a virtual energy state from which a photon is subsequently emitted with the molecule returning to its ground state that explains Rayleigh scattering. In the Stokes situation, the molecule does not return to its ground state but to a vibrational state that is at a slightly higher energy, leading to the emitted photon having a slightly lower energy, or longer wavelength. The final alternative is for the incoming photon to be taken to a virtual energy state but the molecule here is already in a vibrationally excited state and hence the emitted photon has greater energy than the incoming photon and therefore appears at a shorter wavelength.

The end result of Raman scattering is a spectrum for a molecule with a series of discrete wavelengths and this is known as the molecular fingerprint. Using computer-based methods it is now possible to use these spectral fingerprints to identify the molecules present within a sample and hence analyze complex spectra. This has been applied to dental tissue with the first recorded example probably being in 2000 (Hill et al. 2000).

1.3.5 Absorption and Fluorescence

The other major effect that can take place with light and tissue is the absorption of the light (Figure 1.3(e)). Here light of the correct wavelength is absorbed by a molecule either causing an electron to be excited up to a higher energy level, or a change in the molecular vibrational levels in the case of infrared light. The molecule will then lose this energy by one of two routes. In the first, all of the energy will be lost in the surrounding molecules and tissue causing a local heating effect. In the second, there will be a slight loss of energy, and then a photon will be re-emitted containing the remaining energy. This emerging light will be at a longer wavelength than the incoming light and is the well known fluorescent phenomena.

1.3.6 Thermal Emission

Although not really a practical method for any form of dental imaging, thermal emission is included here for completeness. Any material that is above absolute zero will emit some level of electromagnetic radiation, with the wavelength being determined by the temperature. Clearly for light in the visible one is looking for the sample to be several hundred degrees Celsius (red hot coals in a fire) but at lower temperatures the emission is in the mid to far infrared. These temperatures can be seen on a thermal imaging camera and these have been used to investigate clinical challenges in the oral cavity (Kaneko et al. 1999). The problem, however, is that the body is at 37°C and breath from the subject tends to confound the thermal image when applied in a clinical setting. In the oral cavity, hard tissue is slightly fluorescent when excited in the ultra-violet and violet portion of the optical spectrum.