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OPTICAL COHERENCE TOMOGRAPHY AND ITS APPLICATIONS IN ORAL DENTAL DISEASES - A COMPREHENSIVE CLINICAL REVIEW

Oral Pathology

Dr. Avishek Bhandari	Ph.D. scholar, Dept. of Oral & Dental Sciences, JIS University, Agarpara, Kolkata.
Prof .(Dr) R. R.Paul	Professor Emeritus Dept. of Oral & Dental Sciences ,JIS University, Agarpara, Kolkata.
Prof.(Dr) M. Pal	HOD, Dept. of Oral & Maxillo-facial Pathology, GNIDSR, Kolkata.
Prof.(Dr) J.Chatterjee	Dean, JIS Institute of Advance Studies & Research, Kolkata.
Prof.(Dr) M. Majumdar	HOD, Dept. of Oral & Dental Sciences, JIS University, Agarpara, Kolkata.

ABSTRACT

Optical coherence tomography (OCT) is a non-invasive, high-resolution, cross-sectional imaging modality that provides near histologic visualization of biological tissues in real time. Over the last two decades, it has transitioned from an experimental imaging concept into a clinically valuable diagnostic adjunct, initially in ophthalmology and later across other medical and dental specialties. In oral pathology, OCT is increasingly recognized for its ability to detect subtle structural changes in the oral mucosa and dental tissues without the need for invasive biopsy. This review provides a detailed overview of the physical principles, technological evolution, and diverse clinical applications of OCT in oral pathology. It further discusses its role in detecting oral potentially malignant disorders (OPMDs), oral squamous cell carcinoma (OSCC), periodontal and peri-implant diseases, and dental hard tissue assessment. The advantages, limitations, and future research directions, including artificial intelligence (AI) integration and multimodal imaging, are also explored. OCT has the potential to become a routine imaging modality in oral diagnostics, bridging the gap between clinical examination and histopathology.

KEYWORDS

Non-invasive imaging, OCT, OMPDs, OSCC

1.INTRODUCTION

Oral pathology focuses on the identification and characterization of diseases affecting the oral and maxillofacial complex. Accurate and early diagnosis is critical, particularly in diseases such as oral potentially malignant disorders and oral cancer, where prognosis is strongly linked to the stage at detection. Conventional diagnostic approaches include clinical inspection, palpation, radiographic imaging, and histopathological examination of biopsied tissues. While histopathology remains the gold standard for diagnosis, it is invasive, time-consuming, and subject to sampling errors.Modern diagnostic paradigms in oral pathology emphasize **non-invasive and real-time imaging** techniques capable of visualizing structural and functional alterations at microscopic levels. Among such modalities, **Optical Coherence Tomography (OCT)** stands out as a powerful optical imaging technology that uses low-coherence interferometry to produce micrometer-resolution, depth-resolved images of tissue microarchitecture.[1]

Since its development by Huang et al. in 1991 at MIT, OCT has transformed ophthalmic diagnostics and later expanded into cardiology, dermatology, and dentistry. Its application in **oral pathology** is driven by the need for early, painless, and repeatable imaging methods to monitor mucosal and submucosal changes. OCT provides "optical biopsy" capabilities, enabling visualization of epithelial thickness, basement membrane integrity, and subepithelial structures, allowing clinicians to detect abnormalities before they become clinically evident. [1],[2]

2.Principles Of Optical Coherence Tomography

2.1. Basic Physics

OCT employs **low-coherence interferometry**, analogous to ultrasound imaging but using light waves instead of sound. A broadband light source is divided into two beams by a beam splitter: one directed to the **reference mirror** and the other to the **sample (tissue)**. The backscattered light from the sample and the reflected light from the reference mirror interfere when their optical path lengths match within the coherence length of the light. This interference pattern provides depth information from which the cross-sectional image is reconstructed.

The **axial resolution** (depth resolution) depends on the coherence length of the light source, typically 2–15 µm, while **lateral resolution** is determined by the optical focusing system, generally around 10–25 µm. The **imaging depth** is limited to approximately 2–3 mm in highly scattering biological tissues, which is suitable for oral mucosa.[2]

2.2 Image Formation And Data Acquisition

In OCT, a depth profile known as an **A-scan** represents the reflectivity of the tissue as a function of depth. Multiple A-scans are combined laterally to create a **B-scan** (cross-sectional image). Three-dimensional volumetric images can be generated by stacking multiple B-scans. Modern systems utilize **Fourier-domain processing** for faster image acquisition and improved sensitivity compared to early time-domain methods.[2],[3]

3. Types And Technological Evolution Of OCT [1],[2],[3]

3.1. Time-Domain OCT (TD-OCT)

The earliest form of OCT involved mechanically scanning the reference mirror to obtain depth information. TD-OCT, while pioneering, suffered from slow acquisition speeds and limited frame rates, restricting real-time clinical use.

3.2. Spectral-Domain OCT (SD-OCT)

SD-OCT revolutionized imaging speed and sensitivity by replacing mechanical scanning with spectral detection. A stationary reference mirror and spectrometer analyze interference spectra using Fourier transformation, enabling acquisition rates over 100,000 A-scans per second. SD-OCT is widely used in dental and oral imaging research.

3.3 Swept-Source OCT (SS-OCT)

SS-OCT uses a rapidly tunable laser that sweeps across different wavelengths. This configuration provides higher imaging depth, improved signal-to-noise ratio, and the ability to penetrate keratinized tissues-ideal for oral mucosa and submucosal imaging.

3.4 Polarization-Sensitive And Doppler OCT

Advanced variants like **polarization-sensitive OCT** assess birefringence changes in tissues (useful for collagen mapping in oral mucosa), while **Doppler OCT** evaluates blood flow, providing functional insights into inflammatory or neoplastic processes.

4. Clinical Applications Of OCT In Oral Pathology

4.1 Imaging of Normal Oral Mucosa[2]
Understanding normal OCT anatomy is fundamental for identifying pathologic alterations. The oral mucosa displays a **distinct layered architecture** on OCT:
- A highly reflective epithelial layer
- A hyporeflective basement membrane zone
- A moderately reflective lamina propria

Variations in epithelial thickness and reflectivity depend on the degree of keratinization. For instance, buccal mucosa exhibits thin, non-keratinized epithelium, while gingiva shows strong surface scattering due to keratin layers.

4.2 Oral Potentially Malignant Disorders (OPMDs) [3],[9]
Early detection of OPMDs such as leukoplakia, erythroplakia, and oral lichen planus is critical for cancer prevention. OCT allows **non-invasive evaluation of epithelial dysplasia** by visualizing:
- Increased epithelial thickness
- Disruption or loss of basement membrane integrity
- Altered scattering patterns and reduced signal penetration

Clinical studies (Tsai et al., 2008; Wilder-Smith et al., 2009) have demonstrated a strong correlation between OCT features and histopathologic grades of dysplasia. Such real-time imaging can aid in guiding biopsy from the most representative lesion area, improving diagnostic accuracy.

4.3 Oral Squamous Cell Carcinoma (OSCC)[4],[7],[8],[9]
In OSCC, OCT reveals pronounced epithelial irregularity, complete basement membrane destruction, and heterogeneity in backscattering intensity caused by keratin pearls and tumor nests. It can delineate tumor boundaries and help assess surgical margins intraoperatively. Researchers have reported sensitivities up to **90%** in distinguishing malignant from benign oral mucosa using OCT imaging parameters.

OCT may also assist in **post-treatment monitoring** of surgical or radiotherapy sites, allowing early detection of recurrence without repeated biopsies.

4.4 Periodontal and Peri-Implant Diseases[4]
OCT provides non-invasive imaging of soft and hard tissues around teeth and implants. It enables:
- Visualization of gingival sulcus and epithelial attachment
- Evaluation of periodontal pocket morphology
- Detection of early mucosal inflammation and biofilm accumulation

For implantology, OCT facilitates imaging of peri-implant soft tissue integration and microgaps at the implant–abutment interface, supporting early detection of peri-implantitis.

4.5 Dental Hard Tissue Imaging[4],[5]
OCT can detect **incipient enamel caries**, microcracks, and defects at restorative interfaces. Its ability to visualize resin–enamel interfaces aids in evaluating bond integrity and microleakage. It can also monitor demineralization and remineralization processes during preventive dental therapies.

In **endodontics**, OCT assists in examining pulp chamber anatomy and detecting microfractures or internal resorption non-invasively.

4.6 Oral Submucous Fibrosis and Lichen Planus [3],[9]
OCT offers valuable insight into fibrotic mucosal disorders. In oral submucous fibrosis (OSMF), it demonstrates epithelial thinning, increased subepithelial reflectivity, and loss of lamina propria distinction due to fibrosis. Similarly, in oral lichen planus, disruption of epithelial-connective tissue interface and inflammatory infiltration alter backscattering, allowing differentiation from normal mucosa.

4.7 Oral Ulcers And Mucosal Inflammation [7],[8]
OCT enables assessment of ulcer healing dynamics by quantifying epithelial regeneration and angiogenesis. It provides a real-time, quantitative tool to evaluate the efficacy of topical treatments and anti-inflammatory therapies.

5. Comparison With Other Imaging Modalities [1],[3],[9]

Imaging Modality	Principle	Resolution	Penetration	Radiation	Clinical Use
Radiography	X-ray attenuation	Low	High	Yes	Bone & teeth
Ultrasound	Sound reflection	100 µm	Several mm	No	Soft tissue
MRI	Magnetic resonance	50–100 µm	High	No	Soft tissue & TMJ
OCT	Optical interferometry	2–15 µm	1–3 mm	No	Mucosa, teeth

OCT uniquely provides **microscopic detail of superficial tissues**, bridging the diagnostic gap between clinical and histologic examination. It surpasses ultrasound and MRI in resolution for superficial lesions and avoids ionizing radiation exposure.

6. Advantages Of OCT In Oral Pathology
- **Non-invasive and real-time** imaging (“optical biopsy”)
- **Micrometer resolution**, comparable to histology
- **No ionizing radiation**, safe for repeated use
- **Quantitative analysis** of tissue thickness and reflectivity
- **Potential for chairside diagnosis** and longitudinal follow-up

7. Limitations And Challenges
Despite its promise, OCT faces several challenges:
- Limited penetration depth (1–3 mm), restricting imaging of deep lesions
- Difficulty imaging heavily keratinized or highly scattering tissues
- Limited field of view for large lesions
- Interpretation requires specialized training
- High equipment cost and lack of widespread clinical adoption

Future improvements in light sources, detection systems, and signal processing are expected to address these challenges.

8. Future Directions And Clinical Integration
8.1 Artificial Intelligence And Automated Diagnosis
Machine learning algorithms are being trained to classify OCT images of oral lesions based on textural and optical features. AI-assisted OCT could provide real-time diagnostic support to clinicians, reducing interobserver variability.

8.2 Multimodal Imaging
Combining OCT with **fluorescence**, **Raman spectroscopy**, or **hyperspectral imaging** can offer both morphological and biochemical insights, enhancing diagnostic specificity.

8.3 Portable And Intraoral OCT Devices[1],[2]
Recent advancements have led to compact, **handheld intraoral OCT scanners**, making chairside imaging feasible in dental clinics. Integration with digital workflows and CAD/CAM systems will enhance utility in restorative and prosthodontic procedures.

8.4 Clinical Standardization
Future work must focus on establishing standardized imaging protocols, interpretation guidelines, and diagnostic criteria for various oral pathologies to ensure reproducibility and clinical acceptance.

9. CONCLUSION
Optical coherence tomography has emerged as a transformative technology in oral pathology. Its ability to visualize tissue microstructure non-invasively, in real time, with micrometer-scale resolution offers a bridge between macroscopic clinical assessment and microscopic histopathology. Clinically, it enhances the detection of early epithelial dysplasia, malignancy, and inflammatory or fibrotic conditions, while aiding in monitoring treatment response and surgical outcomes.

As OCT technology becomes more accessible and integrated with AI and multimodal systems, it is poised to become a standard adjunctive diagnostic tool in oral healthcare-bringing the vision of “optical biopsy” closer to routine clinical reality.

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