A Review of Radiology and Optical Coherence Tomography in Dental Diagnostics

Hemlata Dewangan [1*], Mahendra Kumar Sahu [1]

Abstract

Background: The rapid evolution of imaging technologies has significantly transformed dentistry, improving the diagnosis and treatment of various dental conditions. While traditional radiological methods such as X-rays and Cone Beam Computed Tomography (CBCT) remain the cornerstone of dental imaging, the emergence of Optical Coherence Tomography (OCT) offers a non-invasive, radiation-free alternative. This review examines the comparative efficacy of X-ray and OCT technologies in diagnosing hard tissue conditions in the oral cavity. Methods: The review analyzed the application of OCT and radiology in dental diagnostics through a custom-built Swept-Source OCT system, assessing its performance against traditional radiological methods. The study utilized both in vivo and ex vivo evaluations, considering variables such as resolution, depth penetration, and image clarity across different dental conditions. Results: OCT demonstrated superior capabilities in detecting early-stage cavities, fractures, and minor imperfections, particularly when high-resolution imaging was required. However, its limited penetration compared to X-rays restricted its application in comprehensive bone assessments. Radiology, especially CBCT, provided essential volumetric data crucial for evaluating bone density, fractures, and post-surgical conditions, though it posed concerns related to radiation exposure. Combining both modalities proved beneficial, offering complementary insights that enhanced overall diagnostic accuracy. Conclusion: While X-ray-based radiology remains indispensable for broad evaluations of dental and bone structures, OCT presents a valuable adjunct, particularly for high-precision assessments of soft tissues and small surface defects. The synergistic use of these technologies can provide a more holistic approach to dental diagnostics, potentially improving patient care and treatment outcomes. Future advancements in OCT could further expand its role in routine dental practice, enhancing diagnostic accuracy while minimizing radiation exposure risks.

Keywords: Dental Imaging, Optical Coherence Tomography, Radiology, Dental Diagnostics, Cone Beam Computed Tomography

Significance | This review assessed the advantages, limitations, and combined efficacy of radiology and OCT in dental diagnostics, enhancing imaging precision.

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Introduction

The field of dentistry has undergone significant transformation in recent decades, primarily driven by technological advancements that enhance the detection and treatment of dental conditions. Various medical imaging techniques, including X-ray radiology, laser-based scanners for cavity detection, and Optical Coherence Tomography (OCT), have emerged as essential tools for diagnosis (Lains et al., 2021). Among these, intraoral and panoramic radiology, along with three-dimensional (3D) Cone Beam Computed Tomography (CBCT), are frequently utilized in routine dental practice (Verhelst et al., 2020). However, concerns surrounding the exposure to ionizing radiation associated with X-

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rays have prompted calls for more cautious use of these technologies. Dental practitioners must ensure that radiation doses are accurately calculated for each procedure, and advancements in X-ray equipment are essential to minimize radiation exposure (Uyan, 2022).

OCT, while more commonly used in fields such as ophthalmology and dermatology, has not yet achieved widespread adoption in dentistry despite its potential benefits (Ali et al., 2021). This imaging technology employs low-power infrared laser light, making it entirely non-invasive and eliminating the risk of radiation exposure for patients, unlike traditional X-ray methods (Won et al., 2020). This review explores the conditions affecting hard tissues in the oral cavity that can be assessed using X-rays, OCT, or a combination of both modalities. It is vital to consider the advantages and limitations of each imaging technique, particularly since OCT's lower penetration level compared to X-ray radiology presents challenges for its application (Moir et al., 2021). Additionally, the quantitative evaluation of dental conditions using specialized software can enhance diagnostic accuracy, enabling practitioners to measure parameters such as cavity depth, secondary decay, and root canal dimensions (Sánchez-Ancajima et al., 2022). By comparing the efficacy of X-ray and OCT methodologies, this review discusses their accuracy in evaluating various dental conditions, utilizing both in vivo and ex vivo assessments to ensure comprehensive analysis (Nabeesab Mamdapur et al., 2019).

2. OCT Model

The review discussed on a custom-built Swept-Source Optical Coherence Tomography (SS-OCT) system, featuring a Master-Slave enhanced configuration, as illustrated in Figure 1. The system employed a laser source operating at 50 kHz, with a central wavelength of 1300 nm and a sweeping range from 1258 nm to 1363 nm. This laser produced an optical beam with a peak power of 20 mW, which was directed into an 80/20 coupler that delivered 25% of the optical power to the sample using a two-dimensional Galvanometer Scanning (GS) system (Dogaru et al., 2024). The backscattered light from the sample retraced its path through the system, merging with the initial light at the coupler. The combined light from both the reference and sample arms was sent to a balanced photodetector, producing interference signals that were then converted into two electrical signals in opposing phases. This process effectively canceled out the slowly varying DC component, isolating the alternating current (AC) component that fluctuated at twice the amplitude of each photodetector signal, resulting from the interference of the sample and reference beams (Bob et al., 2024).

The signal was digitized using a 12-bit waveform analyzer operating at a sampling rate of 500 million samples per second. The resulting digital signal was processed into greyscale images using custom software developed in LabVIEW 2013 (64-bit). This software constructed three-dimensional OCT images and generated en-face (C-scan) images using the Master-Slave (MS) approach, which allowed for the acquisition of en-face images without requiring volumetric reconstructions from B-scans, a common practice in standard OCT systems (Fernández Uceda et al., 2020). The system achieved an axial resolution of 10 μm in air, ensuring precise imaging capabilities.

The OCT device utilized moderate optical power levels, comparable to those used in retinal scanning, typically a few milliwatts. The system demonstrated a sensitivity range between 80 and 90 decibels at line rates of 100 kHz, with the Axsun source operating at 1300 nm and 50 kHz achieving sensitivities exceeding 98 dB when 3.8 mW of optical power was applied to the sample. Although MHz line rates were possible, maintaining safety-required energy levels, it was noted that increasing speed proportionally reduced sensitivity. The MS concept was initially validated using two separate interferometers, the Master and the Slave. Subsequent studies demonstrated that MS could be effectively implemented with a single spectrometer by capturing channel spectra, eliminating the need for an additional interferometer (Fernández Uceda et al., 2020). This approach streamlined the system while maintaining its performance capabilities.

3. *Different Analytical Technology*

3.1. Radiology-Based Dental Analysis

Radiology is a widely used imaging technology in dentistry, essential for diagnosing conditions not visible during standard examinations (Putra et al., 2022). Panoramic imaging, a common radiological technique, is typically the initial diagnostic step as it provides a comprehensive view of the oral cavity in seconds. To ensure accurate detection, patients should undergo both clinical and radiological assessments. While panoramic imaging is useful, it does not suffice for evaluating bone density or assessing postoperative conditions related to bone disorders, such as periodontal issues or fractures. For such cases, a three-dimensional cone beam computed tomography (CBCT) scan is necessary, as it offers qualitative assessments and volumetric data. Figure 2 illustrates a clinical case where CBCT was employed to evaluate a fractured mandible (Verhelst et al., 2020).

3.2. OCT-Based Dental Analysis in Contrast to Radiology

Optical Coherence Tomography (OCT) is increasingly recognized for its superior ability to assess dental conditions such as cavities, cracks, demineralization, and adjustments of restorations or crowns, compared to radiology (Won et al., 2020). Multiple studies have highlighted OCT's advantage in providing more precise detection, especially when high resolution and sufficient penetration are critical. Experiments on dental disorders (Figure 3) demonstrated that OCT images often outperformed radiology in scenarios where detailed visualization was required.

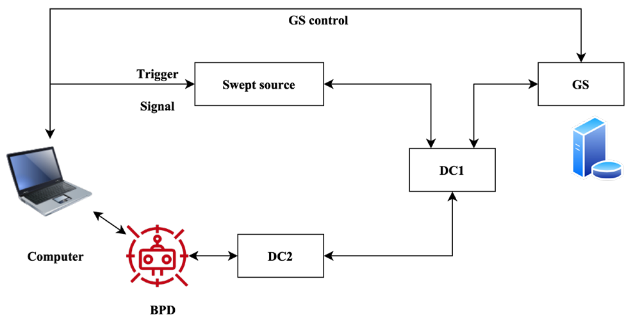

Figure 1. OCT model

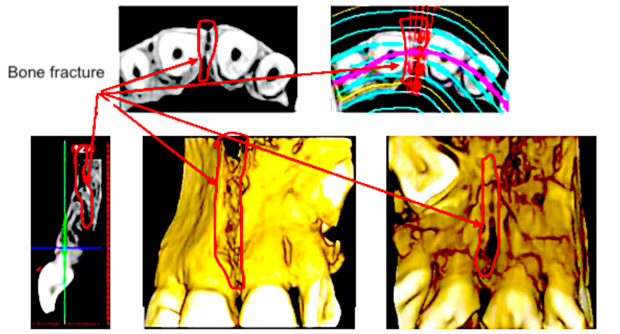

Figure 2. CBCT analysis of fractured mandibular

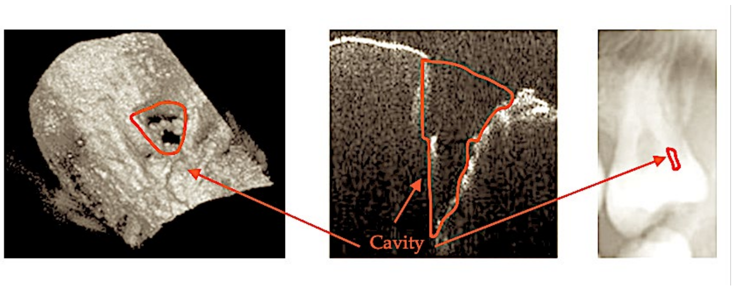

Figure 3. OCT-based cavity detection

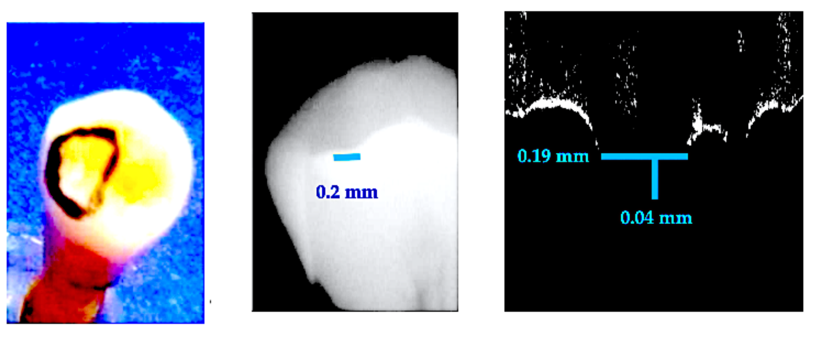

Figure 4. Cavity detection

3.3. Measuring Cavities

This section explores using OCT images to evaluate the clean borders of cavities, comparing the results with those obtained from radiology (Ali et al., 2021). Although radiology maintains consistent resolution across various techniques, specific features visible in the images can vary. Panoramic imaging, for example, may not accurately diagnose small cavities, whereas intraoral radiology can provide more detailed and targeted information. Intraoral radiology's ability to focus specifically on the affected tooth makes it superior to panoramic imaging for detecting small cavities.

Figure 4 compares measures of several cavities, showing that intraoral radiology and OCT provide different outcomes. OCT excels in offering high-resolution, detailed images that are invaluable for precise assessments of smaller dental defects.

3.5. Synergy Between Radiology and OCT

The review discusses a synergistic relationship between radiology and OCT in dental assessments. Both technologies validate each other to some extent and can be used to examine overlapping conditions such as cavities, periodontitis, and the fitting of dental caps or fillings. However, the clarity and information provided by each imaging modality differ, as observed in the cases reviewed.

Radiology and OCT complement each other because some dental conditions are better suited to one technique than the other. Radiology is preferred for examining larger areas and conducting comprehensive evaluations of the entire specimen. In contrast, OCT is ideal for obtaining high-resolution images of smaller surfaces, offering a depth penetration of up to 2 mm within the specimen. Therefore, combining both techniques can provide a more holistic and precise diagnostic approach (Lains et al., 2021).

4. OCT Remarks

Integrating optimization techniques into routine dental imaging processes requires consideration of several critical factors:

Patient-Specific X-Ray Parameters: Different X-ray settings are needed for pediatric, male, and female patients, each requiring tailored radiation doses. For optimal imaging, particularly when the sample undergoes modifications, it is essential to combine OCT with X-ray imaging. This allows for the collection of variables across diverse patient profiles and specific devices.

Anatomical Considerations: The anatomical characteristics of patients can significantly impact radiology outcomes. For instance, overweight patients with increased fatty tissue around the mandible and temporal bones need higher X-ray doses compared to average-weight individuals to achieve clear imaging.

Impact of Dental Materials: The radio-opacity of dental materials used in previous procedures also affects radiographic quality. Patients with numerous metal crowns should receive reduced radiation doses to minimize artifacts caused by the high absorption of X-rays by metallic materials. The study found variations in results among different X-ray units, even though the core imaging process remains consistent. Therefore, each X-ray machine must be calibrated to identify the optimal settings for anode power, current, and exposure duration.

Prevention of Artifacts: Removing jewelry or metal objects from the head or neck region is crucial to avoid artifacts in radiological images.

Advancements in X-Ray Equipment: Modern X-ray equipment continues to evolve, offering improved radiation dose management in alignment with the ALARA (As Low As Reasonably Achievable) principle. Current 3D CBCT images from Planmeca and Soredex devices demonstrate significantly lower radiation doses compared to levels documented two decades ago, highlighting the ongoing progress in radiological safety. Future integration of OCT-based optimization techniques could further enhance the efficiency of X-ray imaging.

Limitations and Advantages of OCT: OCT, which uses IR laser light, cannot penetrate alloys; however, it can still analyze the surface roughness of metals. Unlike other imaging methods, such as 3D CBCT, OCT can capture detailed images near dental caps. This capability positions OCT as a potential alternative to Scanning Electron Microscopy (SEM) for examining metallic cracks. Future research will likely focus on using OCT to investigate metallic components in the oral cavity, such as dental crowns, further expanding its applications in dental imaging.

5. Conclusion

This review has explored the diverse applications of radiology and Optical Coherence Tomography (OCT) in dental medicine, highlighting their respective strengths and complementary roles in evaluating dental conditions and monitoring treatment progress. Radiology remains essential for analyzing bone structures, assessing post-surgical outcomes, diagnosing apical infections, and evaluating root canal fillings. In contrast, OCT offers significant advantages in detecting early-stage cavities, assessing enamel or dentine fractures, and evaluating the condition of metal-based dental caps with high precision.

While radiology remains the dominant imaging technique in dentistry due to its established efficacy, OCT's potential to become a routine complementary tool is evident, particularly for evaluating soft tissue conditions, demineralization, and minor imperfections often missed by traditional X-ray methods. Other specialized imaging techniques, such as Scanning Electron Microscopy (SEM) and confocal microscopy, provide additional insights for specific applications like examining fine apical canal imperfections or researching dental materials.

The review emphasizes the importance of evaluating the advantages and limitations of each imaging approach based on criteria such as image resolution, accuracy, time efficiency, field of view, and potential artifacts. In many clinical scenarios, a synergistic use of both radiology and OCT may offer the most comprehensive evaluation, ensuring optimal diagnosis and treatment planning. Ultimately, integrating OCT into regular dental imaging protocols could enhance diagnostic accuracy and patient care, supporting a more thorough and nuanced approach to dental health management.

Author contributions

HD and MKS contributed to conceptualization, fieldwork, data analysis, drafting the original manuscript, editing, funding acquisition, and manuscript review. Both HD and MKS were involved in research design, methodology validation, data analysis, visualization, and manuscript review and editing. Additionally, HD took the lead in methodology validation, investigation, funding acquisition, supervision, and final revisions. All authors have reviewed and approved the final version of the manuscript.

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Competing financial interests

The authors have no conflict of interest.

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