Innovations in Intraoral Scanning: A Contemporary Review

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ABSTRACT

Intraoral scanners (IOS) represent a monumental leap in digital dentistry, fundamentally transforming the process of capturing three-dimensional (3D) digital impressions of oral structures and largely superseding traditional impression techniques. This comprehensive review meticulously examines the latest advancements in IOS technology, highlighting their increasingly diverse and sophisticated applications across the full spectrum of dental disciplines. We delve deeply into the continuous improvements in accuracy, operational efficiency, and enhanced patient comfort that these devices offer. A significant focus is placed on the transformative integration of artificial intelligence (AI) within IOS platforms, which is enabling unprecedented levels of diagnostic precision, predictive treatment planning, and automated analysis. The article thoroughly explores the utility of IOS in foundational areas such as restorative dentistry, orthodontics, and implantology, while also extending its scope to highly specialized domains like cleft care and forensic odontology. Furthermore, it meticulously details the evolving capabilities of IOS in critical diagnostic functions, including early caries detection, precise tooth shade matching, and the quantitative monitoring of various oral health conditions, such as progressive tooth wear and subtle gingival recession. While acknowledging persistent challenges related to initial investment costs, the learning curve for practitioners, and limitations in certain complex clinical scenarios, the relentless evolution and refinement of IOS technology unequivocally promise a future for dental care that is not only more streamlined and predictable but also profoundly more patient-centric and technologically advanced.

Keywords: Intraoral scanners, digital dentistry, 3D impressions, artificial intelligence, caries detection, orthodontics, prosthodontics, implantology, cleft care, patient experience, digital workflow, teledentistry, forensic odontology, diagnostic tools.

Introduction

The practice of dentistry has undergone a profound transformation in recent decades, largely propelled by a relentless wave of technological innovations. At the forefront of this digital revolution stands the intraoral scanner (IOS), a device that has fundamentally reshaped how dental professionals capture and utilize patient data. For generations, dental impressions, a cornerstone of diagnostic and restorative procedures, were synonymous with uncomfortable, often gag-inducing, and time-consuming processes involving viscous materials and trays. This conventional approach, while effective, was inherently prone to material distortions, patient discomfort, and logistical challenges in transportation and storage. The advent of IOS technology marked a pivotal turning point, offering a sophisticated, non-invasive alternative that captures highly accurate three-dimensional (3D) digital models of the entire oral cavity, including intricate tooth surfaces and delicate soft tissues, directly from the patient's mouth [39].

This shift from analog to digital impression-taking is far more than a mere procedural upgrade; it represents a comprehensive paradigm shift in the entire dental workflow. Digital models generated by IOS facilitate immediate visual feedback for both the clinician and the patient, enhance communication with dental laboratories through seamless digital file transfer, and lay the groundwork for advanced computer-aided design and computer-aided manufacturing (CAD-CAM) processes. This integration into a fully digital chain streamlines every step from diagnosis to final restoration, promising unparalleled precision and efficiency.

Over the past few years, the capabilities of intraoral scanners have expanded dramatically, transcending their initial role as simple impression-taking devices. Modern

IOS platforms are now integrating sophisticated features and artificial intelligence (AI) algorithms, transforming them into multi-functional diagnostic and treatment planning hubs. This evolution is not only refining existing dental procedures but also opening entirely new avenues for patient care, from early disease detection to personalized treatment strategies and remote monitoring.

This comprehensive review aims to synthesize the most recent developments and diverse applications of intraoral scanners, drawing upon a robust body of contemporary research published between 2020 and 2023. We will meticulously explore how these cutting-edge devices are enhancing diagnostic accuracy, optimizing treatment outcomes across a myriad of dental specialties, and ultimately reshaping the very fabric of dental practice. By examining their technological advancements, expanding clinical utility, and the profound impact of AI integration, this article seeks to provide a holistic understanding of the current state and immense future potential of intraoral scanning technology in modern dentistry.

Methods

To provide a comprehensive and up-to-date overview of the recent advancements in intraoral scanners and their multifaceted applications in dentistry, a systematic and rigorous review of the contemporary literature was conducted. The primary sources for this review were a curated list of peer-reviewed articles, with a specific focus on publications from 2020 to 2023. This timeframe was chosen to ensure that the review reflects the most current technological developments and clinical evidence.

Search Strategy and Inclusion Criteria:
The initial selection of articles was based on their relevance to intraoral scanners and their use in various dental contexts. The provided list of references served as the foundational dataset for this review. Each article within this dataset was carefully screened for its direct applicability to the advancements in IOS technology, clinical utility, diagnostic capabilities, integration with other digital tools, and patient/user experience.
Data Extraction and Synthesis:
For each included article, key information was systematically extracted. This included:

- **Study Design:** Identifying whether the study was a systematic review, meta-analysis, randomized controlled trial (RCT), clinical trial, *in vitro* study, *in vivo* study, survey, or case report.
- **Primary Objective:** Understanding the main research question or aim of the study.
- **Key Findings:** Summarizing the most significant results and conclusions.
- **Methodology:** Noting the specific IOS devices used, comparison methods (e.g., conventional impressions, other digital tools), and outcome measures (e.g., trueness, precision, diagnostic accuracy, patient perception).
- **Limitations:** Identifying any acknowledged limitations by the authors that might influence the interpretation of the results.

The extracted data were then synthesized and categorized into thematic areas to facilitate a structured presentation of the findings. These thematic categories included:

- Accuracy and Precision of IOS
- Expanding Clinical Applications across Dental Specialties (Prosthodontics, Orthodontics, Cleft Lip and Palate Care, Periodontics, Endodontics, Forensic Odontology, Maxillofacial Prosthetics)
- Enhanced Diagnostic Capabilities (Caries Detection, Oral Health Monitoring, Developmental Defects, Shade Matching)
- Integration of Artificial Intelligence (AI)
- Patient Experience and Workflow Efficiency
- Specialized and Emerging IOS Applications (Mandibular Kinematics, Teledentistry, Automated Landmark Recognition)

Quality Assessment and Bias Mitigation:
While a formal meta-analysis was beyond the scope of this narrative review, a critical appraisal of each study's methodology and findings was performed. Emphasis was placed on studies with higher levels of evidence, such as systematic reviews, meta-analyses, and randomized controlled trials, where available. Conflicting evidence was noted and discussed to provide a balanced perspective on the current state of knowledge. The aim was to provide an overview of IOS advancements rather than an exhaustive review of all IOS use cases, focusing on the most recent and impactful research.
Ethical Considerations:
As this review is based on published literature and does not involve direct human or animal subjects, no specific

ethical approval was required. However, the principles of academic integrity, including accurate representation of findings and proper citation, were strictly adhered to. This structured approach ensured that the review is comprehensive, evidence-based, and provides a clear understanding of the significant progress and future potential of intraoral scanning technology in modern dental practice.

Results

The extensive review of recent literature unequivocally demonstrates the rapid and substantial progress in the capabilities and widespread adoption of intraoral scanners. These advancements are profoundly impacting various dental workflows, making digital dentistry an increasingly integral part of contemporary oral healthcare.

Advancements in IOS Technology: Hardware and Software Innovations

The evolution of intraoral scanning technology is characterized by continuous refinements in both hardware and software, each contributing to enhanced performance and expanded utility. While detailed proprietary information on specific hardware and software systems is often scarce due to manufacturers' competitive interests, insights from patent databases and published research reveal significant trends.

Hardware Developments:
Initial breakthroughs in IOS hardware focused on achieving faster scanning speeds, eliminating the need for scanning powder, and enabling color image acquisition. These foundational improvements significantly boosted procedural efficiency, elevated patient comfort, and refined the overall user experience. More recently, hardware advancements have been incremental but impactful, driven by a highly competitive market where established brands continually refine their models and new entrants vie for market share by emphasizing either affordability or integrated software solutions [3].
Ergonomics play a crucial role in user preferences, with unique design features distinguishing various IOS models. A notable trend is the shift from traditional corded devices to wireless, battery-powered scanners [3]. This transition offers clinicians increased mobility and convenience, although it introduces considerations regarding reduced operational time and potential connectivity issues. Some advanced models incorporate haptic feedback, providing tactile guidance to the operator during image acquisition, which can improve scanning technique and efficiency. Integrated heaters within most IOS scanning heads mitigate condensation during extended use, ensuring consistent image quality. Furthermore, IOS devices are available as standalone units or as integral components of integrated CAD-CAM platforms, facilitating chairside fabrication of restorations [5]. A significant user-friendly advancement is the implementation of autocalibration in some IOS devices, reducing the need for regular manual calibration and simplifying the workflow.

Despite these advancements, inherent hardware challenges persist. Maintaining a dry operating field remains critical to prevent measurement errors caused by oral fluids, which can distort scan data. Additionally, accurately capturing subgingival preparation margins continues to be a technical hurdle for some IOS systems [51].

Software Innovations:
Software advancements have arguably outpaced hardware in broadening the capabilities of IOS. Modern IOS systems are designed for continuous image capture, employing sophisticated algorithms that seamlessly stitch individual images together to create a complete and optimized 3D digital model. These algorithms often utilize oversampling and average multiple measurement points representing the same area, enhancing the accuracy and detail of the final scan.
Software differentiation is a key competitive factor among IOS manufacturers. While some IOS are primarily designed for basic scanning and data export, others have evolved into comprehensive platforms offering a wide array of software applications beyond simple intraoral impressions. These advanced systems empower dental practitioners to significantly enhance diagnostics, improve patient communication, facilitate precise monitoring of oral conditions, and refine treatment planning. Tailored software applications now encompass diverse functions, including advanced CAD-CAM design, intricate implant planning, aesthetic smile design, and dynamic orthodontic simulations.

Further specialized software enhancements are employed to refine scan data. These include algorithms to eliminate extreme points, thereby minimizing noise and image artifacts that can compromise scan quality. Software also intelligently omits superfluous imaging data, ensuring that extraneous elements like the buccal mucosa and tongue are excluded from the final intraoral impressions, resulting in cleaner and more clinically relevant models.

A pivotal industry shift has been the transition from closed systems, which restricted CAD-CAM workflows to proprietary solutions, to open data interfaces. A recent survey of 21 commonly used IOS revealed that all devices now feature an open interface [3]. This critical development allows for the export of intraoral impression data in at least one standard file format, providing users with unprecedented flexibility, enhanced interoperability with various dental software and laboratory systems, and greater customization options.

Several file formats are used to store intraoral impression data, each with distinct advantages and limitations [52]. The Stereolithography (STL) format, which encodes intraoral impressions as meshes of tessellated triangles, remains the most prevalent file format due to its widespread compatibility and simplicity. In contrast, OBJ (Object) and PLY (Polygon File Format) are more advanced file formats that utilize polygonal facets, freeform curves, and freeform patches for data encoding. These formats offer superior accuracy and, crucially, can store texture and color information, providing a more realistic representation of the oral cavity. While they facilitate easier model modification, they typically require more storage space due to the higher volume of data they accommodate. The "battle of file formats" highlights the ongoing need for standardization to ensure seamless data exchange across different platforms and software.

Three-dimensional (3D) Tooth Segmentation:

The utility of accurate IOS extends far beyond mere image capture, relying heavily on advanced software for in-depth analysis. Precise segmentation of each individual tooth from intraoral impression data is of paramount importance in various applications, particularly in diagnosis and treatment planning within orthodontics, orthognathic surgery, and prosthodontics. This intricate segmentation enables clinicians to perform critical analyses such as space analysis, treatment simulation, movement predictions, and detailed tooth shape analysis [20].

However, tooth segmentation presents significant challenges due to the considerable anatomical variability among patients and the necessity for highly accurate boundary detection between teeth and the surrounding gingiva [20]. This precision is absolutely essential to ensure reliable segmentation outputs, as even minor errors can have cascading repercussions in subsequent treatment planning and execution [20]. Consequently, fully automatic tooth segmentation has historically been a complex computational problem [20, 29].

Traditional tooth segmentation software often relied heavily on extensive, high-quality labeled datasets, which necessitated substantial human effort for manual annotation. This requirement inherently limited the scale and diversity of available datasets [54]. For instance, a fully automated, fault-aware system based on deep learning achieved impressive results in tooth segmentations, with 94% of cases deemed clinically viable by experts without requiring additional corrections [20]. However, this system demanded training with 4,000 intraoral impressions, each meticulously labeled by human experts, underscoring the resource-intensive nature of such approaches.

A novel approach utilizing deep neural networks with unsupervised pretraining followed by supervised fine-tuning has shown promise in achieving precise tooth segmentation in intraoral impressions [28]. This innovative method significantly mitigates the reliance on extensive manually labeled training data, paving the way for more streamlined and scalable tooth segmentation processes. Such advancements are crucial for the continued development and widespread adoption of sophisticated diagnostic technologies within digital dentistry.

Landmarking and Model Analysis:

Manually placing landmarks on dental models, a process essential for diagnostics and outcome assessments in orthodontics, is inherently error-prone and time-consuming. To address this, advanced software solutions have been developed that leverage a combination of machine learning and linear programming to automatically recognize and label each tooth and its specific landmarks [58]. While this automated approach often necessitates human verification for ultimate accuracy, it dramatically facilitates the rapid and precise identification of landmarks on digital dental models. This represents a significant step forward toward the automation of routine clinical evaluations, such as those required for the "Index of Orthodontic Treatment Need."

However, it is important to acknowledge that while automated digital model analyses offer high reproducibility, their results can sometimes differ from those obtained through traditional manual measurements [59]. This highlights a crucial aspect of these automated systems: they provide remarkable rapidity and consistency in results, which are highly beneficial for screening and large-scale assessments. Yet, for certain detailed assessments where the utmost precision and nuanced interpretation are paramount, manual methods may still retain a distinct advantage.

Further software advancements, underpinned by deep learning, enable the categorization of molars within intraoral impressions based on the presence and type of restoration [16]. This represents a foundational step toward creating fully automated systems designed to generate comprehensive dental charts directly from intraoral impressions, significantly reducing manual charting time and potential human error.

Accuracy and Precision of Intraoral Scanners

The accuracy and precision of intraoral scanners remain a central and continually evolving area of research, as these metrics directly impact the reliability and clinical applicability of the digital models. Trueness refers to the degree of closeness of the intraoral impression to the original object, essentially how accurate the scan is compared to reality. Precision, on the other hand, refers to the consistency of repeated scans of the same object, indicating the reproducibility of the device. The root mean square error (RMSE) is a metric increasingly used for assessing accuracy, quantifying the differences between all corresponding points in the reference (actual) and experimental (scanned) models [55]. Lower RMSE values indicate a closer alignment of experimental scans with the reference, signifying high accuracy. While IOS accuracy has generally improved across generations and manufacturers, it's noteworthy that the latest IOS models do not always automatically offer the highest accuracy, suggesting that other factors like operator skill and specific clinical conditions play a significant role [55].

Complete-Arch Scans:

Contemporary IOS achieve clinically acceptable accuracy in scanning complete dentate arches [55]. This is a crucial development, as full-arch impressions are frequently required for various treatments, including orthodontics and extensive restorative cases. However, challenges persist in edentulous areas, where the lack of stable reference points (teeth) can compromise scan accuracy. A systematic review incorporating data from 10 laboratory and 8 clinical studies found that IOS can match the accuracy of conventional impressions for recording denture-bearing soft tissues, particularly in cases where the ridges are firm and have attached mucosa [38]. Despite this, for scenarios like complete denture fabrication or cases necessitating the recording of tissue movements (e.g., functional impressions), existing IOS currently offer no suitable alternative to conventional methods, except for creating preliminary impressions that may require further refinement or traditional techniques for final accuracy.

Implant Impressions:

Dental implants, unlike natural teeth, lack physiological mobility, demanding heightened accuracy from IOS to ensure a passive fit of implant-supported restorations. A systematic review of 8 clinical studies has indicated that contemporary IOS generally meet the accuracy requirements for digital impressions of single or multiple implants [42]. This is a significant achievement, as precise implant position capture is critical for the long-term success of implant prostheses. However, their efficacy in capturing accurate full-arch impressions in complex implant cases, especially those involving multiple implants across an entire arch, remains somewhat limited [55].

To address the challenges of accurately recording the positions of multiple implants, there has been an innovative shift from vertically positioned scan bodies to horizontally positioned scan gauges. These gauges incorporate multiple planes on their top surface, which reduces the need for the IOS to be rotated excessively during scanning. This, in turn, minimizes image stitching errors and positional inaccuracies, leading to more reliable implant capture [18]. The use of scan bodies themselves has been highlighted as a paradigm shift for accurately recording the position of complete-arch implants in a digital workflow, simplifying a previously complex process [18]. Furthermore, stereophotogrammetry systems are also being evaluated for their accuracy in acquiring 3D dental implant positions, offering another promising digital approach [19].

Restorative Accuracy:
For fixed prosthodontic restorations, such as crowns, a review of 12 in vitro and 6 in vivo studies found comparable marginal accuracy between restorations fabricated from IOS scans and those from conventional impressions; both approaches achieved clinically acceptable results [51]. This finding is consistent with earlier reviews on the marginal fit of crowns and 3-unit fixed partial prostheses [5]. Similarly, a systematic review of 8 randomized controlled trials revealed no significant difference in the clinical outcomes of fixed prostheses, whether tooth-supported or implant-supported, between IOS and conventional workflows [30]. These findings collectively substantiate the reliability of IOS in restorative dentistry. However, it is crucial to recognize that substantial variations in accuracy can exist not only between different IOS technologies but also among different generations of a specific IOS, emphasizing the importance of staying updated with the latest device specifications and validation studies.

Expanding Clinical Applications

The utility of intraoral scanners has expanded dramatically, making them indispensable tools across a broad spectrum of dental disciplines. This section details their diverse applications beyond basic impression taking.

Prosthodontics:
In prosthodontics, digital impressions are increasingly becoming the standard for fabricating a wide range of restorations. This includes complete-coverage, fixed tooth-supported prostheses, where systematic reviews have compared their outcomes to those derived from conventional impressions, often showing comparable or superior results [5]. The digital workflow streamlines the design and manufacturing of crowns, bridges, and veneers, allowing for greater precision and customization. Clinical outcomes for both implant-supported and tooth-supported fixed prostheses fabricated from digital versus analogue impressions have been systematically reviewed, consistently indicating favorable results for digital methods, often with improved efficiency [30]. Furthermore, the accuracy of IOS for recording denture-bearing areas in edentulous patients has been systematically reviewed, demonstrating their potential for optimizing complete denture fabrication, especially for preliminary impressions [38]. The ability to capture accurate maxillomandibular relationships is crucial in prosthodontics. While challenging in complex cases, scanning buccal surfaces in maximum intercuspal position has shown higher accuracy for static interocclusal registration compared to full-arch scanning or traditional methods [35]. However, digital bite registration for multispan implant restorations still poses significant challenges [22].

Orthodontics:
IOS have become an indispensable tool in modern orthodontics, offering a critical and often preferred alternative to traditional plaster models derived from conventional impressions [10]. They are central to the increasingly popular clear aligner therapy, where they facilitate precise virtual treatment planning and remote monitoring. The assessment of artificial intelligence-based remote monitoring of clear aligner therapy relies heavily on sequential IOS scans to track tooth movement and aligner fit [17]. This allows for more frequent and convenient check-ups, reducing the need for in-person visits. Despite their widespread use, the presence of fixed orthodontic appliances, such as brackets and wires, can affect the accuracy of intraoral scans [37]. However, recent studies have shown that accurate digital models can still be obtained even with multibracket fixed orthodontic appliances in situ, suggesting that removing brackets and archwires solely for imaging may be unnecessary in many cases [37]. Beyond treatment planning, IOS are also being used for monitoring root position by merging CBCT datasets with pretreatment IOS data, allowing for accurate prediction of root position and potentially obviating the need for additional CBCT imaging during treatment [27].

Cleft Lip and Palate Care:
Digital impressions obtained via IOS are proving invaluable for the management of newborns and preschoolers with cleft lip and palate, offering a significantly less invasive and more comfortable experience compared to traditional methods [6]. IOS are specifically used for creating precise digital impressions

for the fabrication of speech aid/obturators in children, which are critical for speech development and feeding [1]. They also facilitate the virtual, non-invasive construction of nasoalveolar molding (NAM) plates, which are used to reshape the alveolar ridges and nasal cartilage prior to surgical repair [45]. Furthermore, IOS data enable automated, data-driven plate computation for presurgical cleft lip and palate treatment, streamlining the design and fabrication process [43]. An innovative method for 3D capture and analysis of the nasolabial region in cleft cases has also been validated, providing objective data for assessing surgical outcomes and planning revisions [4]. These applications highlight how IOS enhance patient comfort, streamline workflows, and improve outcomes in this sensitive patient population.

Periodontics:

In periodontics, IOS offer precise tools for diagnosing and monitoring periodontal conditions. They can accurately quantify gingival recession using 3D digital dental models, providing objective and repeatable measurements [15]. New computer-aided methods allow for direct measurements and visualization of gingival margin changes, offering a more detailed assessment than traditional probing [24]. Critical reviews are establishing standardized parameters for the digital evaluation of gingival recession, enhancing consistency and comparability across studies and practices [25]. IOS are also used, with the aid of superimposition tools, to monitor soft-tissue changes over time, which is crucial for assessing treatment stability after periodontal surgeries or in cases of peri-implant soft-tissue changes [48]. Clinical and laboratory studies indicate that IOS assessments can surpass conventional techniques in accuracy for these measurements [24]. However, IOS precision in soft tissue evaluation can depend on the operator's skill, the specific device, and the scan location, with interproximal and posterior areas sometimes posing challenges [24].

Endodontics:

IOS contribute significantly to the digital workflow in guided endodontics. By combining IOS data with cone-beam computed tomography (CBCT) scans, clinicians can create precise 3D models of the tooth and surrounding bone, allowing for highly accurate planning of endodontic access cavities and root canal treatments [11]. This guided approach enhances precision in complex procedures, especially in cases with calcified canals or unusual anatomy, minimizing iatrogenic damage and improving treatment predictability.

Forensic Odontology:

A novel and emerging application for IOS is in forensic odontology, where dental records play a crucial role in human identification. The reproducibility of the digital palate using intraoral scanners is being investigated for forensic applications, including sex discrimination and individual identification [34, 47]. The unique morphology of the anterior palate can serve as a highly discriminative feature for distinguishing individuals [34]. Leveraging IOS imaging can significantly speed up and refine the identification process, particularly when pre-existing imaging data are available for comparison.

Maxillofacial Prosthetics:

Beyond intraoral structures, IOS are demonstrating utility in the broader field of maxillofacial prosthetics. Digital auricular impressions using IOS have shown comparable accuracy to conventional methods for ear rehabilitation, streamlining the fabrication of custom ear prostheses [13]. Their utility further extends to capturing nasal, orbital, and other facial defects, although certain larger or more complex defects may still surpass their current scope of applicability [53]. Considering that IOS are generally more accessible and less expensive than dedicated extraoral facial scanners, employing IOS emerges as a promising avenue for innovative digital solutions and cost reductions in maxillofacial prosthetics, particularly for localized or smaller facial defects.

Enhanced Diagnostic Capabilities

Beyond their primary function of impression taking, modern intraoral scanners are increasingly integrating sophisticated features that significantly enhance diagnostic capabilities, offering clinicians new ways to detect and monitor oral diseases.

Caries Detection:

One of the most exciting advancements in IOS technology is the integration of tools for caries detection. These tools are primarily based on two technologies: fluorescence measurements, typically using light with a wavelength of 415 nm, and near-infrared imaging (NIRI), which employs light wavelengths between 727 nm and 850 nm [41].

Depending on the manufacturer's specifications, IOS may support the detection of proximal (between teeth) or occlusal (biting surface) carious lesions, or in some advanced models, both.

Studies have explored the performance of IOS in identifying caries. In a clinical and laboratory setting, an IOS's performance in detecting occlusal caries in permanent molars was compared with visual examination, using histological analysis as the gold standard [32]. The study demonstrated that the diagnostic accuracy of the IOS, utilizing fluorescence measurements, was comparable to that of visual examinations. This finding was corroborated in a subsequent *in vivo* study using the same IOS [36]. Crucially, the IOS exhibited negligible deviation in accuracy between clinical and laboratory conditions, implying consistent performance across different environments [32]. However, this study also highlighted the risk of false-positive results due to the presence of biofilm on occlusal surfaces, underscoring the susceptibility of IOS fluorescence assessments to external factors that can lead to diagnostic errors.

Further evidence comes from a clinical study involving 100 patients, where an IOS capable of simultaneously capturing color images and NIRI data demonstrated non-inferiority to bitewing radiography, with the latter serving as the reference standard [31]. This suggests that NIRI could potentially reduce the reliance on traditional X-rays. Interestingly, experts in assessing scans featuring NIRI achieved higher diagnostic accuracy than novices, indicating a learning curve essential for optimizing the benefits of such features [31].

Despite these promising findings, evidence on the diagnostic accuracy of IOS featuring NIRI remains somewhat equivocal. A laboratory study found that this technology has high sensitivity in detecting enamel lesions, which is advantageous for non-invasive caries management [33]. In contrast, another clinical study showed that a different IOS with NIRI had low sensitivity in pediatric patients, with the most reliable results achieved by combining intraoral impressions with bitewing radiography [12]. This discrepancy suggests that the performance can vary between different IOS models and clinical contexts.

Beyond direct caries detection, IOS can also aid in evaluating developmental enamel defects, such as dental fluorosis and molar-incisor hypomineralization [8]. However, the magnification and color enhancement features of IOS can sometimes lead to an overestimation of the extent of these defects, necessitating careful interpretation [8].

In summary, the growing body of evidence underscores the significant potential of IOS in caries detection. When optimized, these devices can serve as valuable adjuncts to traditional methods, facilitating more reliable and potentially less invasive assessments. By decreasing the reliance on radiographic evaluation, IOS also contribute to reducing patient exposure to ionizing radiation, a significant benefit for long-term oral health monitoring. However, continued research and refinement are needed to enhance their usability and accuracy across all clinical scenarios.

Oral Health Monitoring:

Intraoral scanners are increasingly being utilized for comprehensive oral health monitoring, providing objective and quantifiable data for various conditions.

- **Tooth Wear Monitoring:** Some IOS employ image superimposition software based on best-fit alignment, enabling quantitative assessment of surface alterations over time. In controlled *in vitro* settings, these IOS align closely with profilometric measurements, maintaining an impressive accuracy margin of ±15 µm [57]. This level of precision significantly distinguishes them from traditional semi-quantitative tooth wear indices, which are subjective and less precise. However, the absence of stable oral reference points can make best-fit alignment prone to inaccuracies [9]. While time-consuming strategies exist to mitigate this, such as manually selecting stable reference points or zones, there is an ongoing need for further software enhancements to improve scan registration accuracy, especially in areas with significant tooth loss or extensive restorations. In clinical settings, the repeatability error for IOS tooth wear analyses typically falls between 60 and 70 µm [7]. A discrimination threshold of approximately 73 µm, beyond which measurements are likely to accurately represent true tooth wear, was determined for another IOS in a study using natural teeth [9]. Collectively, these studies indicate that while the measurement technique may provide lower precision for detecting minute levels of wear, it can reliably discern and track changes surpassing specified thresholds, making it valuable for clinical decision-making. Given current accuracy constraints and typical tooth wear rates, periodic intraoral impressions (e.g., every 1-3 years) are valuable for monitoring progression and guiding management strategies [7].

- **Oral Hygiene Assessment:** Planimetric methods, facilitated by IOS, enable the precise quantification of dental plaque coverage, providing a detailed and objective record of a patient's oral hygiene status [14]. A study involving 20 subjects illustrated the accuracy of plaque planimetry using imaging with an IOS after the application of a plaque disclosing agent [23]. This approach facilitated a valid and efficient planimetric evaluation of all tooth surfaces across the entire dentition. It successfully addressed and overcame several limitations inherent to planimetry based on traditional intraoral photographs, showcasing its potential as a superior method for meticulous oral hygiene assessment and patient education. Moreover, a randomized controlled trial revealed significant improvements in periodontal and plaque parameters among patients who used a smartphone for intraoral scanning at home after nonsurgical treatment [46]. In this study, patients received automated motivational messages based on machine learning-supported evaluations of visible supragingival plaque and signs of gingival inflammation. These findings underscore the immense potential of patient-conducted intraoral imaging via smartphones for remote monitoring and personalized oral health counseling, highlighting a promising avenue for enhancing oral hygiene management and patient engagement.

Soft-Tissue Evaluation:
IOS are increasingly being used to accurately assess soft tissue dimensions and changes, particularly in periodontics and implant dentistry. They are employed to evaluate gingival recession and monitor peri-implant soft-tissue stability [24, 25]. With the aid of superimposition tools, IOS can precisely track soft-tissue changes over time, which is crucial for assessing the long-term stability of periodontal treatments or implant sites [15, 48]. Clinical and laboratory studies indicate that IOS assessments can surpass conventional techniques in accuracy for these measurements [24]. However, it's important to note that IOS precision in soft tissue evaluation can depend on factors such as the operator's skill, the specific device used, and the scan location. For instance, acquiring accurate intraoral impressions can be particularly challenging in interproximal and posterior areas due to limited access and potential for scanner tip obstruction [24].

Tooth Shade Determination:
Some IOS equipped with color imaging capabilities are being utilized for tooth shade determination, aiming to streamline the esthetic aspects of restorative dentistry. While some preliminary investigations have suggested that IOS can provide accuracy comparable to visual shade selection, a systematic review found that current IOS often fall short in achieving optimal shade-matching accuracy compared to dedicated spectrophotometers [50]. The discrepancy in shade-matching accuracy between spectrophotometers and IOS primarily stems from IOS's inability to maintain uniform illumination across the scanned area [50]. Additionally, the angle of IOS color readings often deviates from the optimal 0-degree angle, which can introduce further inaccuracies. Consequently, current IOS are generally recommended only as a supplementary tool for tooth shade determination, rather than a standalone definitive method [2]. Further technological advancements are needed to improve the consistency and reliability of color capture under varying intraoral conditions to make IOS a more definitive tool for shade matching.

Integration of Artificial Intelligence (AI)

The integration of Artificial Intelligence (AI) is rapidly transforming intraoral scanning technology, moving it beyond simple data capture to advanced analysis, diagnosis, and treatment planning. AI algorithms, particularly deep learning, are enhancing various aspects of dental practice, making workflows more efficient and precise.

Image Segmentation and Analysis:
AI plays a pivotal role in automating and refining the analysis of intraoral scan data. Deep learning algorithms are being rigorously developed for highly accurate 3D tooth segmentation in intra-oral mesh scans [28, 54]. This involves precisely delineating each individual tooth from the surrounding gingiva and other oral structures. These algorithms utilize complex neural networks trained on

vast datasets of dental scans to learn intricate patterns and boundaries. Both supervised learning (requiring extensive manually labeled data) and unsupervised learning (which can learn from unlabeled data, reducing annotation burden) approaches are being explored [28, 54]. The importance of high-quality labeled datasets for training robust AI models cannot be overstated, as the accuracy of segmentation directly impacts downstream applications like orthodontic treatment planning and prosthetic design [20]. AI-based algorithms are also capable of classifying images of individual molar teeth into categories based on the presence and type of restoration [16]. This capability represents a foundational step towards creating fully automated systems that can generate comprehensive dental charts directly from intraoral impressions, significantly reducing manual charting time and potential human error.

Treatment Planning and Monitoring:

AI is proving to be an invaluable asset in optimizing dental treatment planning and monitoring. In orthodontics, AI assists in the remote monitoring of clear aligner therapy [17]. By analyzing sequential intraoral scans taken by patients (often via smartphone attachments), AI algorithms can track tooth movement, assess aligner fit, and predict the optimal timing for aligner changes. This reduces the need for frequent in-person appointments, enhancing patient convenience and practice efficiency. Similarly, AI is being evaluated for its effectiveness in assisting dental monitoring interventions for patients with periodontitis [46]. By analyzing images of visible supragingival plaque and signs of gingival inflammation, AI-powered systems can provide automated feedback and motivational messages to patients, promoting better oral hygiene practices. AI-based automatic digital model analysis systems are also being rigorously evaluated for their reliability and time-based efficiency in orthodontics, automating measurements and analyses that were previously manual and time-consuming [59].

Digital Twin Creation:

One of the most transformative applications of AI and IOS integration is the creation of "digital twins." These are precise 3D virtual replicas of a patient's oral and maxillofacial anatomy, generated by merging intraoral scans with other imaging modalities such as cone-beam computed tomography (CBCT) scans and 3D facial scans [26, 27]. The effectiveness of creating these digital twins for 3D evaluation of root position during orthodontic treatment is being extensively explored [26, 27]. By overlaying CBCT data (which shows bone and root structures) with IOS data (which shows crown and soft tissue surfaces), clinicians gain a comprehensive, multi-dimensional view of the patient's anatomy. This allows for highly precise and predictive treatment outcomes, particularly in complex surgical planning, implant placement, and interdisciplinary cases. For instance, in guided endodontics, digital twins enable virtual planning of access cavities and root canal paths, ensuring optimal entry and minimal invasiveness [11]. The digital twin concept facilitates a more holistic approach to patient care, allowing for virtual simulations of treatment outcomes, improved communication with patients, and enhanced collaboration among dental specialists.

Patient Experience and Workflow Efficiency

The integration of intraoral scanners into dental practices has brought about significant improvements in both patient experience and overall workflow efficiency. These benefits are key drivers for the widespread adoption of this technology.

Enhanced Patient Comfort:

Perhaps the most immediately noticeable benefit for patients is the elimination of traditional impression materials. The messy, often foul-tasting, and sometimes gag-inducing process of conventional impression taking is replaced by a quick, clean, and non-invasive digital scan. This significantly reduces patient discomfort, anxiety, and the likelihood of gag reflexes [5, 44]. Surveys and clinical studies consistently show that patients rate the comfort of IOS procedures more favorably compared to conventional methods, leading to a more positive overall dental experience [5, 44]. This improved comfort is particularly beneficial for pediatric patients, who often find traditional impressions challenging [44].

Streamlined Workflow and Time-Efficiency:

For dental practitioners, IOS streamline numerous clinical procedures, leading to enhanced efficiency. The immediate availability of digital models eliminates the need for pouring plaster casts, trimming models, and physically shipping them to laboratories. Instead, digital files can be instantly transmitted to dental laboratories, significantly reducing turnaround times for restorations and appliances. This digital workflow, facilitated by IOS, has demonstrated time-efficiency and cost-effectiveness for treatments such as monolithic zirconia implant fixed dental prostheses, as evidenced by randomized controlled trials [22]. The ability to visualize the scan in real-time allows clinicians to immediately identify and correct any missed areas or imperfections, reducing the need for retakes and saving valuable chairside time. This efficiency extends to patient communication, as clinicians can use the 3D models to clearly explain diagnoses and treatment plans, fostering better patient understanding and acceptance.

Adoption and Integration Challenges:

Survey data indicate a growing trend among dental practitioners to either use IOS or actively consider their adoption, with the primary driver being improved clinical efficiency [3, 39]. The fabrication of single-unit restorations is a particularly common initial application for new IOS users [3, 39]. However, despite the clear advantages, the initial investment cost for IOS can be substantial, posing a significant barrier for some practices, especially smaller ones [3, 39].

Furthermore, large dental institutions face unique obstacles in fully implementing and integrating IOS technology. These challenges encompass the complex task of integrating IOS software with existing electronic health record (EHR) systems, ensuring robust data security and patient privacy, managing the extensive data storage requirements generated by large volumes of 3D scans, and providing comprehensive training for clinicians and support staff [21]. Consequently, the adoption of IOS has been observed to be slower in high-volume institutions compared to private practices, where integration complexities might be less pronounced [21]. Addressing these integration and training challenges is crucial for maximizing the benefits of IOS across all dental settings.

Specialized and Emerging IOS Applications

Beyond their core applications in general and restorative dentistry, intraoral scanners are continually finding utility in highly specialized and novel areas, pushing the boundaries of digital dentistry.

Innovations in Prosthodontics: Navigating Complexities with IOSs:

In prosthodontics, accurately recording maxillomandibular relationships is a critical yet often complex step, particularly in challenging cases involving posterior free-end situations (where teeth are missing at the back of the arch without distal support). In patients with a complete natural dentition, scanning the buccal surfaces of a quadrant while teeth are in the maximum intercuspal position has demonstrated higher accuracy in static interocclusal registration compared with full-arch scanning and traditional physical bite recording with polyvinyl siloxane [35]. However, in the context of multispan implant restorations, digital bite registration continues to pose significant challenges, indicating areas for further technological refinement [22].

A significant long-term goal in prosthodontics is the development of virtual articulators derived from patient-specific data, utilizing IOS for dynamic mandibular movement analysis. While progress has been made with improved bite alignment of digital scans, minor translational inaccuracies in mesh alignments can still persist. These inaccuracies, even if subtle, can lead to significant deviations in intercuspal relations, currently limiting their widespread clinical use for highly precise occlusal adjustments [40].

Given the persistent challenges of obtaining consistently accurate complete-arch intraoral impressions of implants, alternative methods such as photogrammetry are garnering increasing attention. Photogrammetry involves capturing high-resolution photographs of implants from various angles, using screw-retained fiducial markers as references. This method employs advanced software to identify common points across the photographs to construct highly accurate 3D models of dental implant positions. While capturing adjacent teeth and soft tissues still requires an additional impression (either via an IOS or conventional methods), a systematic review suggests that photogrammetry may serve as a reliable alternative for obtaining implant scans, particularly for fully edentulous arches [19]. However, it is important to note that the evidence substantiating this is currently limited and primarily stems from studies focusing on implants in fully edentulous arches, warranting further research for broader applicability.

Orthodontics: The Digital Shift:

The widespread adoption of orthodontic aligners for treating various malocclusions has significantly increased, and concurrently, intraoral impressions and virtual treatment planning have become highly practicable alternatives to conventional workflows [10]. This digital shift has revolutionized how orthodontic diagnoses are made and how treatment strategies are formulated. However, evidence on the accuracy of orthodontic measurements derived from digital methods versus traditional plaster casts remains somewhat conflicting [10]. These discrepancies appear to vary based on the specific type of IOS used, highlighting the importance of device-specific validation.

Orthodontics often necessitates full-arch scans, frequently involving crowded teeth and existing orthodontic appliances, which can pose unique challenges for digital impressions. Despite these complexities, a study involving 20 adolescents demonstrated that accurate digital models can be obtained from IOS scans taken even with multibracket fixed orthodontic appliances *in situ* [37]. This suggests that the cumbersome process of removing brackets and archwires solely for imaging may be unnecessary in many clinical situations, further streamlining the orthodontic workflow.

Beyond diagnostics and treatment planning, IOS are also being innovatively used for monitoring root position during orthodontic treatment. By merging CBCT datasets (which provide detailed information about root anatomy and position within the bone) with pretreatment IOS data (which capture crown morphology), highly detailed 3D tooth models can be generated [27]. These integrated models, when combined with digital scans taken during or after treatment, permit accurate prediction of root position changes, potentially obviating the need for additional CBCT imaging throughout the treatment process and reducing patient exposure to radiation [27].

Oral and Maxillofacial Surgery: Expanding IOS Utility:

Similar to orthodontics, IOS are finding increasingly varied and critical applications in oral and maxillofacial surgery (OMFS). Retrospective studies from multiple cleft care centers have demonstrated the successful and safe application of IOS across diverse age groups, from neonates to preschoolers [6, 56]. These studies included individuals with cleft lip and palate as well as other congenital craniofacial disorders, showcasing successful IOS use in patients whether they are awake or under general anesthesia. IOS are proving versatile for comprehensive diagnostics, precise treatment planning, and the accurate fabrication of orthopedic appliances in OMFS. For instance, IOS can be used to fabricate customized appliances for nasoalveolar molding (NAM) for infants, which are crucial for presurgical reshaping of the alveolar ridges and nasal cartilage [45]. They are also used for creating speech-enhancing obturator prostheses in children with cleft lip and palate deformities, significantly improving quality of life [1].

Beyond improving airway safety during impression taking (a common concern with traditional methods in OMFS patients), IOS streamline workflows and facilitate the integration of additional digital technologies. This includes the automated design of presurgical orthopedic plates and the quantitative assessment of upper lip scarring and asymmetry, providing objective metrics for surgical outcomes [4, 43, 60].

In addition to cleft care, laboratory studies have illustrated that IOS can digitize facial defects to clinically acceptable levels, potentially rivaling the scanning accuracy of more expensive extraoral optical systems [13, 53]. Considering that IOS are generally more accessible and less expensive than dedicated extraoral facial scanners, employing IOS emerges as a promising avenue for innovative digital solutions and cost reductions in maxillofacial prosthetics, particularly for localized or smaller facial defects. However, it is crucial to acknowledge that the capabilities of IOS have inherent limitations: certain extensive or complex defects, such as large orbital defects, may still surpass their current scope of applicability, necessitating the use of other imaging modalities [53].

Teledentistry: IOSs for Remote Care:

The ability of IOS to generate high-quality digital models facilitates seamless data sharing among dental professionals, which is a cornerstone of teledentistry. This enables remote assessments, consultations, and collaborative treatment planning, expanding access to dental care, especially in underserved areas or for patients with mobility limitations. The findings of an observational diagnostic accuracy study suggest that remote assessments based on approximate true-color intraoral impressions can be effective in detecting various dental findings [49]. However, their accuracy in evaluating periodontal conditions remotely was found to be inconsistent [49]. Improved image quality, coupled with the integration of supplementary patient data such as radiographs and clinical notes, could significantly potentiate IOS as efficient tools for patient screening and triage in teledentistry, enabling more effective remote diagnostic capabilities.

Furthermore, the use of smartphones for patient-conducted intraoral imaging presents significant potential benefits for identifying issues like orthodontic aligner unseats and determining the optimal timing for aligner changes. This empowers patients to actively participate in their treatment monitoring from home. However, a retrospective study found that while promising, the evaluated system was not yet suitable for use by itself, emphasizing the ongoing need for periodic in-person monitoring and continued technological improvements to ensure reliable remote care [17].

Forensic Dentistry: A New Frontier for IOSs:

Similar to teledentistry, IOS are also finding novel ground in the specialized field of forensic dentistry. Dental records are of paramount importance for forensic identification, and the unique morphology of the anterior palate can serve as a highly discriminative feature for distinguishing individuals [34, 47]. Leveraging IOS imaging can significantly speed up and refine the identification process, particularly if pre-existing digital imaging data of the individual are available for comparison [34]. The ability to create precise, reproducible 3D models of the palate offers a powerful tool for forensic analysis, potentially reducing the time and resources required for identification in complex cases. The reproducibility of the digital palate using intraoral scanners has been investigated in forensic contexts, including a two-year retrospective cohort study on twins, highlighting its potential for reliable identification [34].

Digital Twins: Enhancing Comprehensive Treatment Planning

The concept of "digital twins" represents a significant leap forward in comprehensive dental treatment planning, made possible by the integration of highly accurate intraoral scanners with other advanced imaging modalities. These digital twins are precise three-dimensional (3D) virtual models that provide an exact anatomical replica of a patient's oral and maxillofacial structures, encompassing intricate details and complex spatial relationships [26]. This integration fundamentally enhances the accuracy, efficacy, and predictability of a wide range of dental procedures.

The creation of a digital twin typically involves merging intraoral impression (IOI) data with cone-beam computed tomography (CBCT) scans and, in some cases, 3D facial scans. Each modality contributes unique information: IOS provide highly detailed surface anatomy of teeth and soft tissues; CBCT offers comprehensive insights into bone structure, root morphology, and pathology; and 3D facial scans provide a realistic representation of the patient's facial aesthetics. The seamless registration and superimposition of these datasets create a holistic virtual patient model.

This integrated digital twin serves as a powerful platform for advanced treatment planning across various disciplines:

- **Digital Smile Design:** By combining IOI data with 3D facial scans, clinicians can perform digital smile design, allowing them to virtually plan and visualize aesthetic changes to the patient's smile in harmony with their facial features. This enhances patient communication and allows for predictable esthetic outcomes.
- **Guided Implant Surgery:** The merger of IOS scans with CBCT data is foundational for both static and dynamic navigation methods in implant dentistry [11]. Static guides (surgical templates) are 3D-printed based on the digital twin, ensuring precise implant placement according to the pre-planned position, angle, and depth. Dynamic navigation systems, which provide real-time guidance during surgery, also rely on the accurate registration of the patient's anatomy with the digital twin. This significantly reduces surgical risks, enhances predictability, and optimizes restorative outcomes.
- **Endodontic Access Cavities:** In endodontics, digital twins support guided endodontics, particularly for complex cases such as calcified canals or unusual root anatomy. Virtual planning of the endodontic access cavity based on the CBCT imaging, combined with the IOS surface data, ensures optimal entry and minimal invasiveness. A suitable sleeve system can be designed to accurately guide the bur, and a custom guide can be planned to secure the sleeve system, incorporating inspection windows to verify

accurate placement (Fig. 4). This approach minimizes iatrogenic damage and improves treatment predictability [11].

- **Orthodontic Mini-Implant Placement:** The precise 3D information from digital twins is invaluable for planning the optimal placement of orthodontic mini-implant (temporary anchorage devices), which are used to provide stable anchorage for tooth movement.
- **Tooth Autotransplantation:** Digital twins facilitate the complex planning required for tooth autotransplantation, where a tooth is moved from one position in the mouth to another. The precise 3D models allow for accurate assessment of donor and recipient site compatibility, optimizing the surgical procedure and improving success rates.
- **Root Position Evaluation:** The effectiveness of creating digital twins with different digital dentition models and CBCT scans for 3D evaluation of root position during orthodontic treatment is being explored [26, 27]. This allows orthodontists to visualize root movement within the alveolar bone, which is critical for avoiding root resorption and ensuring stable treatment outcomes.

The digital twin concept extends beyond static planning to dynamic analysis. While still in early stages, the goal is to develop virtual articulators from patient-specific data, using IOS for dynamic mandibular movement analysis [40]. This would allow for the simulation of chewing movements and occlusal contacts, leading to more functional and harmonious restorations.

In essence, digital twins transform complex anatomical data into an actionable, interactive virtual environment, empowering clinicians with unprecedented control and insight into their patients' oral health. This comprehensive approach not only enhances the accuracy and efficacy of various dental procedures but also significantly improves patient understanding and engagement in their treatment journey.

Discussion

The findings from the extensive recent literature unequivocally demonstrate that intraoral scanners (IOS) have transitioned from being a novel technology to a fundamental and indispensable component of contemporary dental practice. This evolution signifies a profound paradigm shift, moving away from conventional analog workflows towards highly efficient, precise, and patient-centric digital processes. The continuous advancements in IOS hardware, software, and their integrated functionalities are driving this transformation, making digital dentistry an increasingly sophisticated and accessible reality.

The consistent improvement in the **accuracy and precision** of IOS is a cornerstone of their growing acceptance. Studies confirming their reliability for full-arch scans, implant impressions, and the fabrication of various prostheses [5, 30, 42, 55] directly translate to tangible clinical benefits. Better-fitting restorations and appliances require fewer chairside adjustments, significantly enhancing patient satisfaction and reducing overall treatment time. The ability to capture highly precise 3D data is particularly advantageous for complex cases, such as those involving cleft lip and palate. For these vulnerable patient populations, IOS offer less invasive and more comfortable impression-taking experiences, while simultaneously providing superior data for intricate surgical and orthopedic planning [1, 4, 6, 43, 45]. The shift towards horizontally positioned scan gauges for multiple implants also highlights a continuous drive for improved accuracy in challenging scenarios [18].

The **expanding clinical applications** of IOS across virtually all dental specialties underscore their versatility. In prosthodontics, they streamline the creation of crowns, bridges, and dentures. In orthodontics, they are central to aligner therapy and efficient treatment monitoring. Their utility in periodontics for precise gingival recession monitoring and soft tissue evaluation provides objective data for longitudinal assessment. The integration into endodontics for guided procedures and their emerging roles in forensic odontology and maxillofacial prosthetics further illustrate their broad and growing impact.

One of the most significant leaps forward is the integration of **enhanced diagnostic capabilities** directly into IOS platforms. Features like Near-Infrared Transillumination (NIRT) for caries detection [12, 31, 32, 33, 36, 41] represent a move towards earlier, non-invasive identification of carious lesions, potentially reducing reliance on ionizing radiation from traditional radiographs. While a learning curve exists for optimal interpretation and some discrepancies in sensitivity have been noted across different devices and patient groups (e.g., pediatric patients), the potential for early intervention is substantial. Similarly, the capacity to quantitatively monitor oral health conditions such as tooth wear [7, 57] and gingival recession [15, 24, 25] provides clinicians with objective, quantifiable data for personalized preventive strategies and long-term patient management. The systematic review confirming the role of IOS in accurate shade matching [2, 50] further streamlines the esthetic aspects of restorative dentistry, although current limitations suggest they are best used as a supplementary tool.

Perhaps the most exciting and rapidly evolving area is the increasing **integration of Artificial Intelligence (AI)** with intraoral scanning technology. AI-powered algorithms are revolutionizing data processing, enhancing tooth segmentation [20, 28, 54], automating image classification [16], and transforming remote monitoring of orthodontic treatments [17, 59]. The concept of "digital twins," created by merging IOS data with CBCT scans [26, 27], is particularly transformative. These comprehensive 3D virtual models enable unprecedented levels of precision in surgical planning, allowing for virtual simulations of treatment outcomes and a more holistic understanding of complex anatomical relationships. AI applications not only improve diagnostic accuracy by automating tedious tasks but also significantly enhance efficiency by providing clinicians with valuable, data-driven insights, freeing up time for patient interaction and complex decision-making.

From the **patient's perspective**, the benefits are clear: reduced discomfort, shorter chairside time, and a more engaging experience through real-time visualization of their oral structures [44]. This positive patient perception is a significant driver for the adoption of IOS in private practices. For clinicians, the **workflow efficiency** gains are substantial, from instant digital file transfer to laboratories to reduced need for retakes. However, the integration of IOS into large dental institutions has faced challenges, including compatibility with existing electronic health record systems, extensive data storage management, and the need for comprehensive staff training [21]. These logistical hurdles can slow adoption, highlighting the need for more seamless interoperability and scalable training solutions. The "battle of file formats" [52] from different intraoral optical scanners also presents a persistent challenge for seamless data exchange and full integration across diverse digital platforms.

Emerging applications further highlight the versatile and evolving nature of IOS technology. Preliminary studies exploring mandibular kinematics [40] suggest potential for dynamic occlusal analysis. The growing interest in **teledentistry** [49], where IOS facilitate remote diagnoses and patient-conducted imaging via smartphones, promises to expand access to care and enhance patient engagement in their own oral hygiene management [46]. Furthermore, the novel application of IOS in **forensic dentistry** for human identification based on palatal morphology [34, 47] demonstrates the unexpected breadth of their utility.

Despite these remarkable advancements, challenges remain. The initial investment cost for IOS can be substantial, posing a barrier for some practices, particularly smaller ones or those in developing regions. While patient comfort is generally improved, the learning curve for operators to achieve optimal scanning technique and integrate the digital workflow effectively can be steep [21]. Specific clinical scenarios, such as scanning highly reflective surfaces (e.g., highly polished restorations) or areas with excessive moisture, may still present difficulties, although ongoing technological refinements are continuously addressing these issues. The need for robust data security and efficient data management systems also becomes more critical as practices accumulate vast amounts of sensitive patient data.

Future directions for intraoral scanners are poised for continued innovation. We can anticipate further miniaturization of scanner heads, leading to even greater patient comfort and improved access to posterior regions. Increased scanning speed and enhanced software capabilities for real-time analysis and immediate feedback will further streamline workflows. Even more sophisticated AI integration is expected, moving towards predictive analytics for disease progression, personalized treatment recommendations, and potentially automated quality control during scanning. The expansion into augmented reality (AR) and virtual reality (VR) applications, where clinicians could interact with digital twins in immersive environments, holds immense promise for surgical planning and patient education. Furthermore, the potential for robot-assisted procedures guided by IOS data represents a compelling research frontier, offering the possibility of unprecedented precision in dental interventions. As the digital ecosystem in dentistry continues to mature, intraoral scanners will undoubtedly play an increasingly pivotal role in shaping a future for oral healthcare that is not only more efficient and accurate but also profoundly more patient-friendly, technologically advanced, and globally accessible.

Conclusion

Intraoral scanners have undeniably emerged as a cornerstone technology in contemporary dentistry, fundamentally reshaping clinical workflows and elevating the standards of patient care. Their evolution from simple impression-taking devices to sophisticated diagnostic and planning platforms represents a monumental achievement in digital dentistry. By offering precise digital impressions, IOS have significantly enhanced accuracy and efficiency in restorative dentistry, orthodontics, and implantology, while simultaneously improving patient comfort by eliminating the need for traditional, often uncomfortable, impression materials.

The integration of advanced diagnostic capabilities, such as near-infrared transillumination for early caries detection and quantitative tools for monitoring tooth wear and gingival recession, has transformed IOS into powerful diagnostic instruments. Furthermore, the rapid integration of Artificial Intelligence, particularly deep learning algorithms, is revolutionizing image analysis, tooth segmentation, and treatment planning, leading to the creation of comprehensive "digital twins" that enable unprecedented precision and predictability in complex procedures.

While challenges related to initial investment costs, operator learning curves, and seamless integration into large institutional systems persist, the benefits derived from IOS in terms of improved clinical outcomes, enhanced patient experience, and streamlined workflows are undeniable. The continuous innovation in IOS technology, driven by advancements in hardware, software, and the transformative power of artificial intelligence, promises to further elevate diagnostic precision, optimize treatment efficiency, and ultimately improve the quality and accessibility of dental care for patients worldwide. As digital dentistry continues to mature, intraoral scanners will remain at the forefront, shaping a more advanced, efficient, and patient-centric future for oral healthcare.

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