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Tomorrow's Grin: A Comprehensive Review of the Next Era in Orthodontic Advancements

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Abstract

The field of orthodontics is experiencing rapid evolution driven by technological advancements. Traditional treatments like metal braces are being replaced by more discreet options such as clear aligners, with further innovation anticipated. Personalized medicine, incorporating genetics and biotechnology, will tailor treatments to individual patient needs, potentially through genetic testing and biocompatible materials. Artificial Intelligence (AI) is set to optimize treatment planning and outcomes by analyzing vast patient data, while digital technologies like 3D printing and intraoral scanners promise streamlined workflows and enhanced precision. Overall, these developments promise a future of orthodontics characterized by greater effectiveness, comfort, and customization for patients. Hence, this article will explore the transformative potential of these advancements, highlighting their role in offering patients orthodontic treatments characterized by greater effectiveness, comfort, and customization.

Keywords: Orthodontics, Technological advancement, Future of Orthodontics, Artificial Intelligence.

Introduction

Orthodontics, a branch of dentistry dedicated to correcting dental and facial irregularities, has indeed undergone remarkable advancements in recent years, promising an even more transformative future. As technology continues to advance at a rapid pace, the landscape of orthodontics is poised for further innovation. One significant trend shaping the future of orthodontics is the continual development of new technologies and treatments. From the traditional metal braces to more discreet options like clear aligners, the options for patients have expanded dramatically. Looking ahead, we can anticipate even more sophisticated and customizable orthodontic solutions.

Personalized medicine is another area expected to play a pivotal role in the future of orthodontics. With advancements in genetics and biotechnology, orthodontic treatments are likely to become increasingly tailored to individual patient needs. This could involve genetic testing to predict treatment outcomes more accurately or the use of biocompatible materials to enhance treatment efficacy and patient comfort. Artificial Intelligence (AI) stands out as a game-changer in orthodontic care. AI-powered algorithms can analyze vast amounts of data to optimize treatment planning and predict patient outcomes with unprecedented accuracy. Additionally, AI-driven software can assist orthodontists in identifying patterns and trends in patient data, leading to more informed decision-making and improved treatment outcomes.

Furthermore, the integration of digital technologies such as 3D printing and intraoral scanners is expected to streamline orthodontic workflows and enhance treatment precision. 3D printing allows for the fabrication of custom orthodontic appliances and models, while intraoral scanners eliminate the need for messy impressions, making the treatment process more comfortable and efficient for patients. In summary, the future of orthodontics holds great promise, fueled by advancements in technology, personalized medicine, and AI. These innovations are set to revolutionize the field, offering patients more effective, comfortable, and tailored orthodontic treatments than ever before.

Future of diagnostic procedure

Diagnosis involves identifying the nature of a problem, disease, or condition through the examination of the patient's history, along with their symptoms and signs. This process requires compiling a comprehensive and precise database of pertinent information to fully understand the patient's issue and address any uncertainties the clinician may have regarding treatment. Proper diagnosis is the crucial initial step in achieving treatment goals for managing any clinical condition**(Fig 1**). In recent decades, orthodontics has significantly embraced digital technology. Orthodontists have reaped substantial benefits from the digital era, notably in boosting productivity and cutting labor costs[1]. New technologies continually emerge, aiding practitioners in understanding patient issues, diagnosing, planning treatments, and executing these plans with greater precision. Software programs have enhanced the accuracy, simplicity, and efficiency of diagnosis and treatment planning.

Digital impression and study model

Digital impressions have revolutionized impression-taking, partly replacing traditional methods like alginate and PVS (Polyvinyl Siloxane). Intraoral scanners offer numerous benefits, including reduced patient discomfort, increased time efficiency, simplified clinical procedures, and the ability to capture and store highly accurate data. These scanners enhance orthodontic diagnosis and treatment planning by allowing for easy and fast electronic data transfer, immediate access, and reduced storage space **(Fig 2).** Digital dentistry, particularly through the use of intraoral scanners, is also reshaping the dentist-dental laboratory relationship. Digital impressions streamline treatment ergonomics by facilitating a seamless flow of information within the office and between patients and dental laboratories. The first 3D hand-held intraoral scanner, OraScanner™, was developed by OraMetrix Company in the USA.

Also, Plaster study models are essential for orthodontic diagnosis, treatment planning, case presentations, and record-keeping but are difficult to transport and store. Digital models **(Fig 3)**, though more expensive, offer minimal storage space and costs, making them a superior alternative.

Laser Scanningand3Dmd Imaging Systems

Laser scanning 3D imaging technology is used for facial soft tissue imaging. The image is taken at 0.5-mm sensitivity and for 8–10 seconds. The length of time obtaining images may cause stabilization distress and loss of the image clarity, especially in infants and young patients. Recently, especially in the dental clinic, 3dmd (3Dmd, Atlanta, Ga, USA) face system, which is a stereophotogrammety system, has been started to be used frequently. 3dmd is a surface imaging system and designed to display a 3D human face**(Fig 4)**. The system provides exact size image with face morphology and linear, angular, and volumetric measurements of the human face[2]. Advanced photography speed with high resolution eliminates image distortion caused by patient movement

Laser holography: Laser holography, a new method for measuring tooth movement, provides an accurate, noninvasive method for determining movement in three dimensions. The stresses generated in the periodontium when the crown of a tooth is subjected to a force have important implications for the study of orthodontic tooth movement and periodontitis. **(Fig5).**

Artificial intelligence: AI research aims to achieve human-like generality, leveraging its pattern recognition capabilities for diverse applications in imaging diagnostics. A notable recent innovation is using AI for extraction prediction in orthodontic planning. Despite its development starting in 1943, the term "artificial intelligence" was coined by John McCarthy at a 1956 Dartmouth conference. Accurate 3D views enable precise 3D printing for customized treatment plans.[3] Algorithms analyze data to intelligently adjust pressure for moving teeth [effectivel7y]. AI alignment devices streamline treatment, simplifying programming and enabling precise monitoring.

Sensors In Treatment Planning: In orthodontics, FMS (Force Monitoring Systems) are utilized to track tooth movement during treatment.[4,5] Strain sensors, attached to teeth surfaces, detect changes in tooth strain as they shift, informing treatment adjustments for optimal results **(Fig 5)**. Piezoelectric sensors gauge forces exerted by teeth on brackets or appliances, offering precise data. Strain gauges also measure bracket or appliance deformation under force application, aiding in determining force distribution and magnitude.

Temporary Anchorage devices: The key to successful treatment of various malocclusions is "Secure Anchorage." Absolute anchorage, characterized by no movement of the anchorage units, can only be achieved with ankylosed teeth or dental implants[10]. As per Cope, a temporary anchorage device (TAD) is a bone-fixed device used to enhance orthodontic anchorage, supporting the reactive unit's teeth or eliminating the need for it entirely, and later removed. Bone-based anchorage units, including miniscrews and miniplates, collectively termed temporary anchorage devices (TADs), fulfil this role.

Role of Gene Therapy in Achieving Precision Orthodontics: Gene therapy as a genetic engineering technique has the potential to make possible the prevention of many antenatal, congenital, and postnatal genetically induced dentofacial anomalies, including dental malocclusion. The gene therapy experiments in orthodontic treatment are still emerging and limited to cell cultures or animal experiments

Gene Therapy for Tooth Movement Modulation: Orthodontic tooth movement relies on remodeling the periodontal ligament and alveolar bone, mediated by cells like osteoblasts, osteocytes, osteoclasts, and the periodontal ligament (PDL). Osteoclasts and osteoblasts, originating from hemopoietic and stromal cell precursors respectively, govern this process. Their interaction, mediated by receptor activator of nuclear factor kappa-B ligand (RANKL), plays a key role[5,6]. Gene therapy experiments using Osteoprotegrin (OPG) and RANKL have shown promise in modulating tooth movement, with local RANKL gene transfer accelerating movement and local OPG gene transfer inhibiting it. These findings hint at a potential shift in orthodontic treatment, with the possibility of shorter treatment times and improved outcomes.

Gene Therapy in Repair of Root Resorption and Retention Stability: Researchers used a viral envelope packaging system to conduct an experiment on OPG gene transfer in rats, aiming to prevent orthodontic relapse[8]. Local OPG gene therapy inhibited osteoclastogenesis, reducing relapse after tooth movement. Additionally, the impact on orthodontic root resorption was examined using microcomputed tomography and histological analyses. While no significant difference in root resorption was found between the start and end of tooth movement in the OPG gene therapy group, it demonstrated superior repair compared to control groups.Application in human is still a scope of further research.

Limitations and Challenges of Gene Therapy: At present, the application of gene therapy in clinical practice is limited by its biosafety concern. The success expected from gene therapy depends on its delivery system. For the delivery of the gene, either viral or nonviral vectors may be used as carriers. Viral vectors provide efficient gene delivery to the targeted tissue cells and longer duration of gene expression[9]. Nevertheless, use of viral vectors for transgenesis is still doubted to be hundred percent safe and free of adverse side effects. Due to safety concerns associated with viral vectors such as immunogenicity and oncogenicity. Despite these challenges and biosafety issues, some promising successful stories of gene therapy are emerging in the field of dentistry[11-15]. Ongoing research in the gene therapy field provide an optimistic future for dentistry field especially for precision orthodontics. The application of gene therapy in orthodontics has just seen the beginning of an era of immense potential and possibility.

Lasers in orthodontics: Lasers find various applications in orthodontics, including expediting tooth movement, debonding ceramic brackets, enamel etching for bonding, pain relief post-orthodontic force, preventing enamel demineralization, and performing procedures like frenectomy and operculectomy. Laser irradiation induces changes in enamel such as recrystallization and melting, creating numerous pores and bubble-like inclusions, making it suitable for enamel etching[16]. Laser etching also results in fractured, open dentin tubules and an uneven surface, ideal for adhesion.

Applications of lasers in orthodontics

1. Diagnostic-
(a) Laser Scanning
(b) Laser Holography
2. Soft tissue management-
(a) Gingivectomy
(b) Gingivoplasty
(c) Laser Exposure of the superficially impacted teeth for bonding attachment
(d) Other applications of the laser soft tissue procedures in orthodontics- frenectomy, operculectomy, circumferential fiberotomy, ablation of minor aphthous ulceration, excision of soft tissue lesions.
3. Low-level diode laser(Photobiomodulation)
(a) Lasers for orthodontic pain reduction

(b) Lasers for the acceleration of orthodontic tooth movement.

4. Other Applications-

(a) Laser Welding

(b) Laser etching

(c) Lasers in caries prevention

(d) Lasers in debonding

Keeping constant development, limitations, hazards and safety of lasers in mind, lasers can have a wide range of scope and convenience in orthodontic practice.

Future of material in orthodontics

Nanomaterials Application in Orthodontics: Nowadays, nanotechnology plays an important role in the dental field since it has the potential to bring significant innovations and benefits. The recent positive results are a stimulus for future research, especially regarding orthodontics[17]. The range of research including orthodontic bonding materials, covering of brackets and wires, as well as their antimicrobial characteristics has a huge potential. Nanoparticles can be successfully added to acrylic resins, cements, or orthodontic adhesives to prevent enamel demineralization during orthodontic treatment.

Antimicrobial coating on materials: The presence of orthodontic appliances leads to an imbalance in the oral environment and an increase in the number of pathogenic bacteria associated with enamel demineralization and periodontitis[18-19] .However, antibacterial mouthwash or toothpaste cannot provide long-term sustained antibacterial effect, and modified adhesives existing between the base of the bracket and the surface of the enamel only have limited antibacterial effect. Therefore, in order to provide long-term sustained antibacterial effect, antibacterial modification of orthodontic appliances themselves is warranted.

Robotics in orthodontics: In the realm of orthodontics, education and training have been revolutionized by robotics, mirroring the broader conceptual and technological advancements in the field. Over the past decade, significant progress has been made in robotic wire bending and customization of CAD/CAM appliances, enhancing the precision and efficiency of arch wire bending and treatment. The pioneering Sure Smile robot, introduced by Butscher et al. in 2004, paved the way for other robots utilized in various customized CAD/CAM appliances such as Sure Smile, Incognito, LAMDA, Insignia, and BRIUS[20].

Advances in scanning and automation technology have enabled the consistent fabrication of dimensionally accurate, custom-made, and removable orthodontic appliances in large quantities. Align Technology, for instance, employs stereolithography technology to produce reference models, which are then processed through an automated aligner-forming system. These models are then trimmed and customized with laser precision using automated cutting machines. Robotic applications extend beyond appliance fabrication to implant placement and maxillofacial surgeries, including cleft palate surgeries, where they enhance surgical efficiency and precision.

Robots are actively involved in treating Temporomandibular Joint Disorder (TMD) through massage robots, mouth opening robots, and neurological rehabilitative exoskeleton robots. These technologies encourage patient engagement and accurately monitor progress through progressive therapy routines. Additionally, nanorobots have been explored in animal studies to accelerate tooth movement using nanoelectromechanical systems (NEMS) and nano LIPUS ultrasound devices. Furthermore, the concept of smart brackets with integrated nanomechanical sensor systems has shown promise in real-time measurement of 3D force and moment, enabling orthodontists to apply force with precision.

Conclusion

Orthodontics has seen significant growth in the past decade, driven by technological advancements in brackets, bonding agents, imaging systems, and the use of mini-implants, expanding its scope to the use of robotics and virtual reality.

1. Digital technology has greatly benefited orthodontists, enhancing productivity and reducing labor costs by aiding in diagnosis, treatment planning, and implementation for more accurate outcomes.
2. Recent advances in biomechanics aim to achieve faster and more controlled tooth movement using discrete appliances, such as temporary anchorage devices and "smart" archwires.
3. While technological advancements have revolutionized orthodontic treatment, it's essential to recognize that no technology can replace the dedication and hard work of human clinicians.
4. Despite progress, there is still room for improvement in bridging the gap between knowledge and practice, focusing on personalization, outcome simulation, and biologically induced acceleration of tooth movement.

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Legend Figures

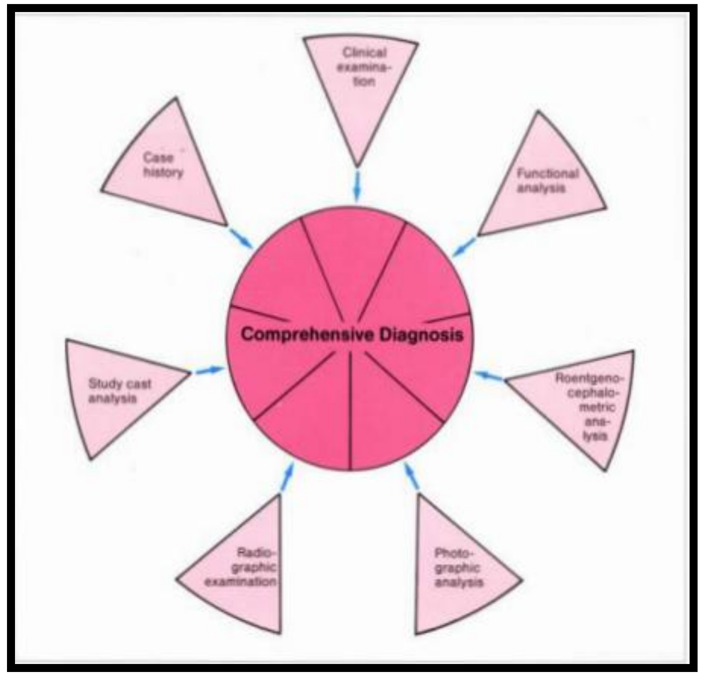


Figure 1: Essential parts of Comprehensive Diagnosis

	Conventional Methods	Intraoral Scanning	Conflicting Results
Stress		✓	
Fear		✓	
Feeling of comfort		✓	
Pleasant feelings		✓	
Queasiness		✓	
Gag reflex		✓	
Taste/smell/heat		✓	
Painless		✓	
Breathing difficulty		✓	
Dry mouth		✓	
Powder and related feelings			✓
Perception of time			✓
Tooth/gingival sensitivity		✓	
Overall opinion/preference			✓

✓: Greater acceptability of the specific method of impression.

Figure 2:Specific aspects of person-reported preferences & experiences.

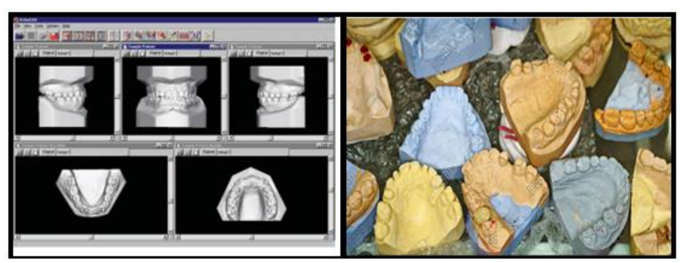


Figure 3: A) Gallery 3-dimensional model images in Ortho CAD, B) Plaster study models

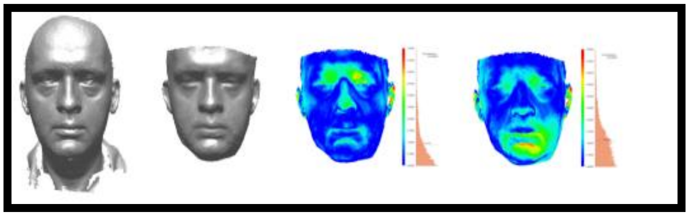


Figure 4: 3d MD face scan, face photogrammetric reconstruction, and their ICP-based and bowbased registrations

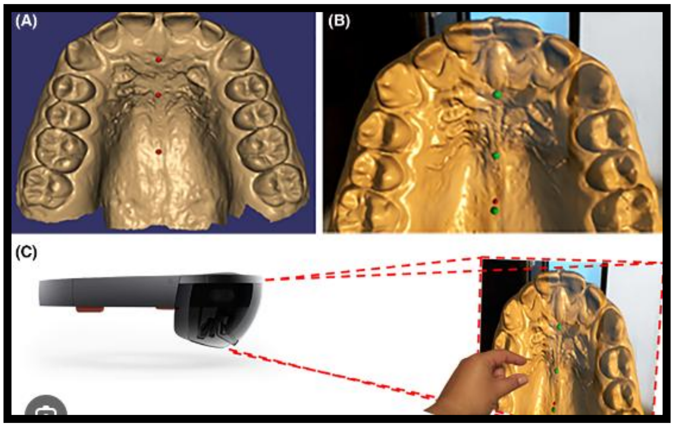


Figure 4: Laser Holography

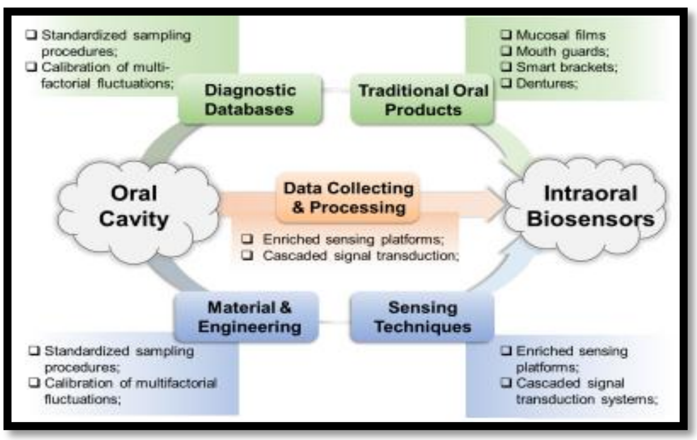
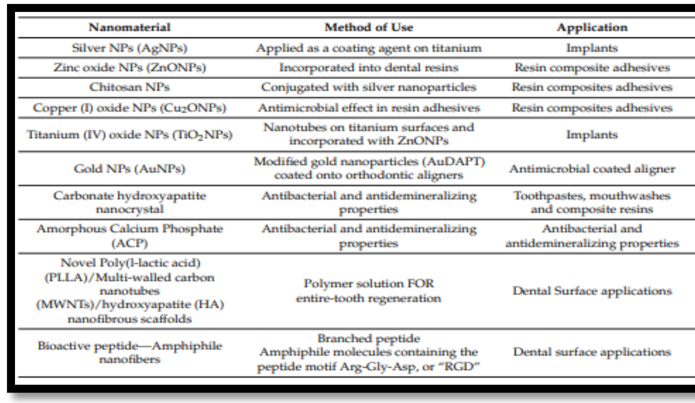


Figure 5: Multi-disciplinary approaches for developing intraoral biosensors.



Nanomaterial	Method of Use	Application
Silver NPs (AgNPs)	Applied as a coating agent on titanium	Implants
Zinc oxide NPs (ZnONPs)	Incorporated into dental resins	Resin composite adhesives
Chitosan NPs	Conjugated with silver nanoparticles	Resin composites adhesives
Copper (I) oxide NPs (Cu_2ONPs)	Antimicrobial effect in resin adhesives	Resin composites adhesives
Titanium (IV) oxide NPs (TiO_2NPs)	Nanotubes on titanium surfaces and incorporated with ZnONPs	Implants
Gold NPs (AuNPs)	Modified gold nanoparticles (AuDAPT) coated onto orthodontic aligners	Antimicrobial coated aligner
Carbonate hydroxyapatite nanocrystal	Antibacterial and antidemineralizing properties	Toothpastes, mouthwashes and composite resins
Amorphous Calcium Phosphate (ACP)	Antibacterial and antidemineralizing properties	Antibacterial and antidemineralizing properties
Novel Poly(l-lactic acid) (PLLA)/Multi-walled carbon nanotubes (MWNTs)/hydroxyapatite (HA) nanofibrous scaffolds	Polymer solution FOR entire-tooth regeneration	Dental Surface applications
Bioactive peptide—Amphiphile nanofibers	Branched peptide Amphiphile molecules containing the peptide motif Arg-Gly-Asp, or "RGD"	Dental surface applications

Figure 6: Nanomaterials Application in Orthodontics

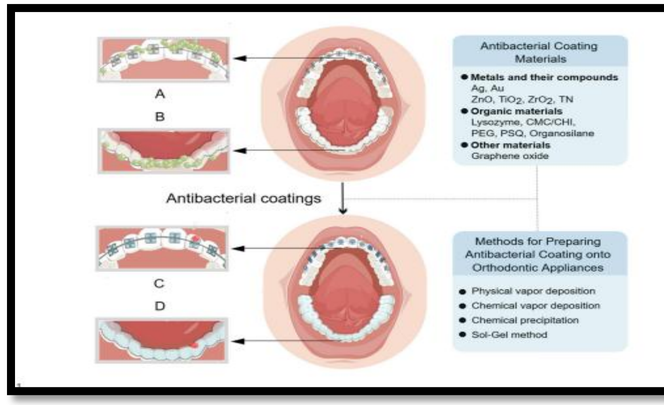


Figure 7: (A) Bacteria build up on the surface of fixed appliance before the application of coating. (B) Bacteria build up on the surface of clear aligner before the application of coating. (C) Bacteria on the fixed appliance are reduced after coating. (D) Bacteria on the clear aligner are reduced after coating

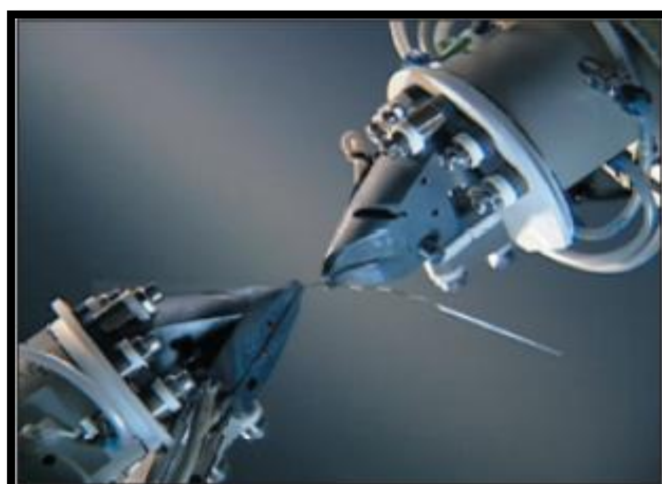


Figure 8: Wire bending using Robots