Unique Features of Nanomaterials and their Combination Support Applications in Orthodontics

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Nanotechnology is a rapidly evolving field with numerous biological applications and is becoming increasingly significant due to its immense potential to enhance the properties of orthodontic and biomaterials. It is employed in various emerging areas of orthodontics, focusing on improving the performance of diverse orthodontic appliances and accessories, as well as nanoelectromechanical systems (NEMS) and nanorobots. Nevertheless, the biocompatibility and cytotoxicity of nanomaterials in orthodontic applications require further investigation. This paper reviews the latest applications of nanomaterials in orthodontics, elucidates their unique features and synergistic applications in orthodontics, and outlines prospective developments in the field.

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Nanotechnology is an interdisciplinary field that encompasses the manipulation, precise positioning, modelling and fabrication of materials at molecular and atomic scales. The concept of nanotechnology was first introduced by American physicist and Nobel Prize laureate Richard Phillips Feynman, while the term “nanotechnology” itself was coined in 1974 by Norio Taniguchi[1,2].

Nanomaterials are defined as materials with components smaller than 100 nm in at least one dimension and may include grains, fibres, atomic clusters, films, nanoholes or combinations of these forms. One-dimensional nanomaterials are known as sheets, two-dimensional nanomaterials are referred to as nanowires and nanotubes, and 3D nanomaterials are called quantum dots[3]. As material size decreases to the nanoscale, the smaller particle size enables enhanced permeation into deeper lesions. The surface–volume ratio rises dramatically with the reduction in material size, which in turn improves catalytic activity and alters physical and chemical properties. Both the internal tiny diameter of nanowires or nanorods and the perfection of facets of the nanostructure contribute to the enhancement of mechanical strength. Mechanical strength increases with decreasing size, but only when the diameter is less than 10 microns[4]. Nanofabrication can be achieved through two approaches: the top-down approach, which employs miniaturisation techniques to create micro-/nanoscale structures from macroscopic materials, and the bottom-up approach, which involves constructing macroscopic structures from atoms or molecules that possess self-organising or self-assembling capabilities[5].

Nanomaterials, with their smaller particle size, can be readily incorporated into orthodontic materials for the purposes of modification. For instance, they can serve as material coatings to reduce friction[6,7], alter hydrophilic and hydrophobic properties[8] or impart antibacterial properties as functional coatings[9].

Over the past decade, nanotechnology has shown promising applications in enhancing dental treatment and care and prevention of oral diseases[10]. The superior inherent characteristics of nanomaterials compared

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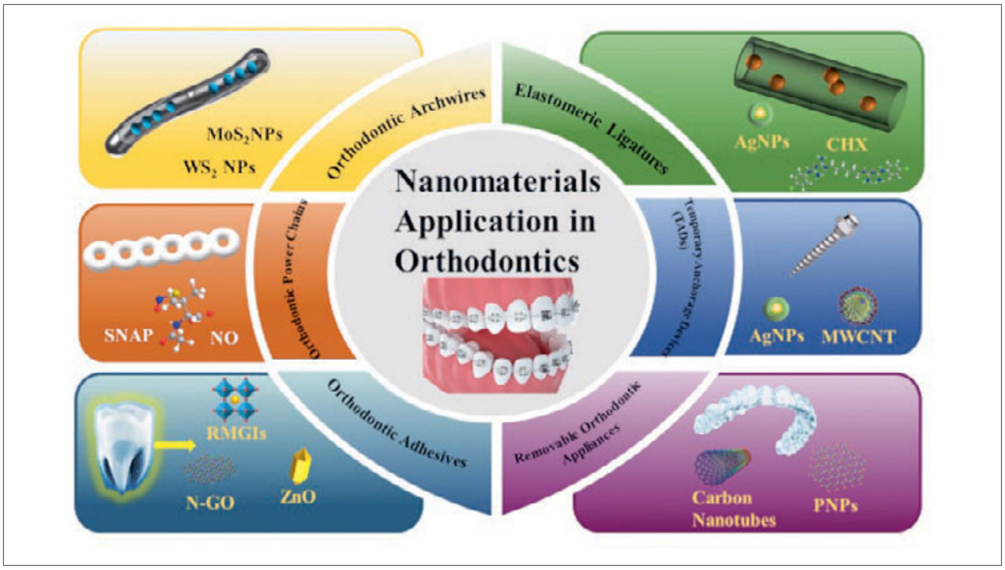

Fig 1 Application of nanomaterials in orthodontics.

to conventional materials allow them to be used in a broad range of clinical dentistry applications, such as periodontics, endodontics, oral and maxillofacial surgery, prosthetics, preventive dentistry and orthodontics[11].

This article focuses on recent innovative applications of nanotechnology in orthodontics, including nanocoating of orthodontic archwires[6,12-16], nanoparticle (NP)-delivering elastomeric ligatures[17-20], property-enhanced power chains via nanoimprinting[8,21], integration of NPs in orthodontic adhesives, and use of shape memory nanocomposite polymers[22-33]. Temporary anchorage devices (TADs) modified with nanotechnology and nanoelectromechanical systems (NEMS) improve orthodontic tooth movement[34-44].

Nanotechnology has optimised the properties of orthodontic materials significantly, reduced treatment duration, increased patient satisfaction and brought numerous benefits to orthodontics; however, further research is necessary to investigate the biocompatibility and cytotoxicity of NPs[45]. There is an urgent need to conduct safety risk assessments and prevent potential side effects.

Application of nano-optimised materials in orthodontics

Generally, nano-optimised materials, as compared to conventional orthodontic materials, exhibit superior properties for clinical use in orthodontics, particularly in terms of antibacterial characteristics and enhanced mechanical properties (Table 1). The predominant applications in orthodontics are outlined in Fig 1.

Nanocoating of orthodontic archwires and brackets

A primary challenge faced in orthodontic biomechanics is reducing friction between the archwire and the bracket. Employing excessive orthodontic force to counteract friction may lead to root resorption and anchorage loss, necessitating the minimisation of friction between the archwire and bracket to expedite tooth movement and shorten the treatment duration[12].

NiTi archwires boast the highest corrosion resistance, shape memory effect and superelasticity; however, prolonged use may result in erosion by active saliva, and the subsequent release of nickel ions could be harmful, as it could cause local swelling, taste disorders, allergies and even the induction of pre-malignant lesions in the oral mucosa structure[13,46].

To mitigate friction between the archwire and bracket and minimise the release of sensitising nickel ions, NP coatings on archwires have emerged as an effective solution. MoS_2 (molybdenum disulphide) and WS_2 (tungsten disulphide) nanomaterials are particularly well-suited for coating applications due to their lubricating properties[6]. They feature a unique layered structure, consisting of a hexagonal crystal (H) of the metal Mo/W intercalated between two layers of anionic sulphur atoms, yielding synthetic 2H-MoS_2 and 2H WS_2, respectively. Van der Waals forces between the synthesised layers are relatively weak, resulting in an unstable structure that readily bends and folds in on itself. As observed in transmission electron microscopy images of these NPs, the structures exhibit concentric layers encircling a hollow core measuring 10 to 100 nm. This distinctive structure renders the WS2/MoS2 nanocoat-

Table 1 Optimised properties of orthodontic materials through nanotechnology support applications in orthodontics.

Applications in orthodontics	Current limiting factors	Optimised properties of orthodontic materials	Materials in nanotechnology	Reference
Orthodontic archwires and brackets	Friction between archwires and brackets; release of potential hazards	Lower friction; limited release of sensitising metal; antibacterial and anti-inflammatory properties	MoS_2 NPs, WS_2 NPs	6
			Clove and cardamom reinforced ZrO_2 NPs	14
			TiO_2 NPs	13, 15
			Graphene sheets embedded carbon (GSEC)	12, 16
			Ag NPs	15
Elastomeric ligatures	Accumulation and retention of bacterial plaque; degradation of mechanical properties caused by bacterial by-products	Long-term antibacterial properties; embedded NPs in the elastomeric matrix	Ag NPs	19, 20
			Chlorhexidine hexametaphosphate (CHX-HMP)	17, 18
Orthodontic power chains	Discolouration; reduction of elasticity	Hydrophobic property; maintained surface and mechanical properties; antimicrobial properties	Anodic aluminium oxide (AAO)	8
			S-Nitroso-N-acetyl penicillamine (SNAP)	21
TADs	Bacterial colonisation around miniscrews; weakened intimacy and stability to the bone caused by autoclaving; excessive bone resorption and inhibiting bone regeneration caused by titanium-type materials; low survival rates and removal torque values (RTVs)	Antibacterial properties; enhanced matrix mineralisation; rapid osseointegration on the bone–implant surface; better biocompatible properties; reduced pressure-holding effect; enhanced early osseointegration; higher bone–implant contact (BIC) ratio	Ag NPs	43, 44
			Multiwalled nanotubes (MWCNTs)	42
			Hydroxyapatite (HA)	41
			HA/collagen nanocomposite (Hap/Col)	40
			Polyetheretherketone-nano HA (PEEK-HA)	39
			TiO2 nanotube	38
			Drug-loaded nanotube arrays	37
			ZnO NPs	36
Orthodontic adhesives	Accumulation of oral biofilm; enamel demineralisation, white spot lesions	Reduced surface roughness; enhanced long-term optical properties; superior mechanical properties; stronger antimicrobial and remineralisation capabilities	Ag NPs	29
			Chitosan NPs (CNPs)	28
			Cinnamon NPs	27
			ZnO NPs	26
			NPs of calcium fluoride (nCaF2) and dimethylamino hexadecyl methacrylate (DMAHDM)	25
			Nano-HA	23, 24
			Nano-graphene oxide (N-GO)	22
Removable orthodontic appliances	Contain bacteria caused by surface porosities; increased risk of candidiasis and stomatitis	Improved mechanical properties and thermal conductivity; antimicrobial properties	Nano-graphene	63
			Carbon nanotubes	64
			Propolis NPs (PNPs)	60
			Gold nanoclusters	65

ing an exceptional solid lubricant, transforming sliding friction into rolling friction while maintaining stable tribological properties under high loads[6]. Previous research has demonstrated that the sliding friction resistance of archwires coated with Ni-P and inorganic fullerene-like WS_2 (IF) NPs was significantly diminished in an oral environment simulated with deionised water[47]. Archwires coated with cobalt and IF-WS_2 NPs, produced via electrochemical codeposition, displayed a 66% reduction in the friction coefficient compared to their uncoated counterparts[6].

In the most recent study, graphene sheets embedded carbon (GSEC) film coating demonstrates a low friction coefficient (0.12) and exceptional wear resistance[12]. As the substrate bias voltage increases from +5 to +50 V, the local microstructures of carbon films fabricated using the electron cyclotron resonance plasma sputtering system transition from amorphous carbon to graphene nanocrystallites. The development of a salivary adsorbed layer and graphene sheet-rich tribofilm on the contact interfaces contributes to the enduring low friction performance of GSEC film-coated archwires (exceeding 30 days)[12].

Given the toxicity of WS_2, alternative NPs, such as carbon nitride (CNx), ZnO and nanoceramics, have been employed. Recent research has revealed that coatings of clove and cardamom-reinforced zirconium oxide NPs exhibit strong antibacterial and anti-inflammatory properties. Notable antimicrobial activity against *Lactobacillus*, *Streptococcus mutans*, *Staphylococcus aureus* and *Candida albicans* has been detected. Furthermore, minimal cytotoxicity suggests improved applicability for orthodontic archwires; however, due to the absence of in vivo testing, additional studies are required to confirm clinical efficacy[14]. Silver- and nitrogen-doped TiO_2 NPs have also demonstrated antimicrobial capabilities when applied to orthodontic archwires[13].

Delivering NPs from elastomeric ligatures

Orthodontic elastomeric ligatures, composed of polyurethane or latex, offer advantages such as ease of application, diverse colour options, reduced patient discomfort and cost-effectiveness[48]; however, they are prone to bacterial plaque accumulation and retention, which can result in enamel demineralisation and white spot lesions. Moreover, bacterial by-products compromise the ligatures' mechanical properties. During orthodontic treatment, elastomeric ligatures firmly secure the archwires within the brackets. These ligatures can function as a carrier scaffold for NP delivery, embedding an elastic matrix with anti-inflammatory/antibiotic drug molecules and anti-cariogenic fluoride[49].

Prior research has demonstrated the synthesis of silver NPs (AgNPs) in situ on orthodontic elastomeric ligatures, providing antibacterial properties against *Streptococcus mutans*, *Staphylococcus aureus*, *Lactobacillus casei* and *Escherichia coli*[20]. NPs enhance the permeability of bacterial cytoplasmic membranes, disrupting the bacterial envelope by continuously releasing silver ions. Additionally, they interact with sulphur and phosphorus within DNA, hindering DNA replication, cell reproduction and protein synthesis[50]. Consequently, silver NPs eliminate microorganisms effectively and reduce the enamel demineralisation rate. Furthermore, elastomeric ligatures incorporating AgNPs can release silver ions for up to 4 months, providing long-lasting antibacterial effects with excellent biocompatibility and no adverse impact on mechanical properties[19].

Recent in vitro studies have demonstrated that chlorhexidine hexametaphosphate (CHX-HMP) enables a sustained release of soluble chlorhexidine (CHX) from orthodontic elastomeric ligatures for over 8 weeks following ethanol pre-treatment, without compromising the mechanical properties of the ligatures[18]. As a cationic compound possessing broad-spectrum antibacterial activity, CHX has emerged as a crucial component in oral preparations, such as mouthrinse and oral gel, as well as an antimicrobial agent. In the form of digluconate salt (CHXdg), CHX is highly soluble in water, thus facilitating its incorporation into water-based local preparations. In contrast, CHX-HMP exhibits lower solubility, which results in sustained release. Although CHX concentrations in the oral environment are insufficient to present a health risk, it is important to consider the potential for drug resistance and adverse reactions when designing NP delivery systems to achieve targeted release[17].

Orthodontic power chains: Nanoimprinting and nitric oxide–releasing technologies

Since the 1960s, power chains have been widely employed in orthodontic treatment. Primarily composed of polyester or polyether polymers derived from rubber, these chains are connected by urethane bonds [-(NH)-(CO)-O-]. In clinical orthodontic practice, they are valued for their flexibility, cost-effectiveness and adjustability; however, their susceptibility to changes in the oral environment (temperature, pH and moisture absorption) can lead to discolouration and diminished elasticity due to water absorption. To address these issues, some researchers have fabricated nanostructures on orthodontic power chains using nanoimprinting with anodic aluminum oxide (AAO) templates as mould inserts. Subsequent surface treatments revealed an increased contact angle of power chains (from 80 to 130 degrees), causing them to transition from hydrophilic to hydrophobic. Surface modification resulted in a 2% decrease in water absorption rate, enhancing surface properties and reducing colour adhesion on the orthodontic power chains[8].

A study conducted by Warden et al[21] explored the potential of a novel nitric oxide (NO)–releasing polymer and nanotechnology. NO is an endogenous gaseous free radical with antimicrobial properties, demonstrated to prevent biofilm formation and effectively inhibit the growth of oral microorganisms such as *Streptococcus mutans* and *Lactobacillus casei*. S-Nitroso-N-acetyl penicillamine (SNAP) serves as a synthetic NO donor that can be successfully integrated into elastomeric power chains. These chains release NO within 3 days, suppressing *Streptococcus mutans* growth for the initial 24 to 48 hours; however, the number of SNAP molecules loaded into the chains and the polymer network interactions within the material may impact the elastic properties of the chains. Future research should aim to extend NO release duration, minimise cytotoxicity and preserve the mechanical properties of orthodontic power chains[21].

Nanotechnology as applied in TADs

TADs, comprising miniscrews, mini-plates and prosthodontic dental implants, are well-suited for most orthodontic applications due to their ability to withstand forces up to 300 g[51]. Although TADs offer absolute anchorage control with minimal patient compliance and enable the reciprocal force of anterior retraction to be transmitted to the alveolar bone without affecting the posterior teeth[39], their high failure rate (15% to 30%) poses a challenge for clinicians[36,42]. An ideal TAD should possess two key features: reduced insertion torque to minimise bone damage, and improved holding power to prevent premature loss[52]. Factors such as bone integration at the bone–implant interface and bacterial colonisation around the micro-implants may influence the characteristics of TAD and the treatment outcomes achieved. Consequently, minimising inflammation is crucial for the long-term stability and success of implants.

Autoclaving, which employs steam within the range of 121°C to 134°C, has become the most prevalent and reliable method for sterilising instruments and devices used in medical treatment; however, repeated autoclaving can alter the microstructure of TADs, diminishing their integration and stability with the bone. After assessment, AgNPs solution demonstrated antibacterial activity against *Porphyromonas gingivalis* comparable to that of autoclaving, while also preventing damage to the devices caused by autoclaving[43]. By coating micro-implants with an AgNP-coated biopolymer (Ti-BP-AgNP), research has shown that the modified implants exhibited strong antibacterial properties (against *Streptococcus mutans*, *Streptococcus sanguini*, and *Aggregatibacter actinomycetemcomitans*), confirming their potential as excellent implantable biomaterials[44].

One study aimed to evaluate the impact of surface roughness and carboxyl functionalisation of multi-walled carbon nanotubes (MWCNTs) combined with collagen coatings on titanium substrates, as well as their subsequent effects on osteoblast responses. The results indicated that both MWCNT and MWCNT-COOH (which renders the surface hydrophilic and wettable) coatings increased surface roughness and enhanced osteoblast (MC3T3-E1) proliferation and differentiation, and matrix mineralisation in vitro; however, the latter proved more effective. Earlier research corroborated the cytocompatibility of MWCNTs, suggesting that their functionalisation warrants further investigation[42]. Additionally, nanotopography and hydroxyapatite (HA) have been demonstrated to synergistically promote osteoblast adhesion, proliferation, differentiation and osseointegration. Following anodic oxidation (AO) with HA coating, the modified TADs' surfaces exhibited upregulated gene expression of osteogenic and adhesion markers such as osteopontin (OPN), osteocalcin (OCN), vinculin and collagen type 1 (COL)[41].

In conjunction with these previous findings, a recent study reported that the thickness of a bone-like hydroxyapatite/collagen nanocomposite (Hap/Col) coating can be controlled effectively using a modified electrophoretic deposition (EPD) technique incorporating Mg^{2+} ions, resulting in higher adhesive strength[40]. The Hap/Col-coated Ti substrate prepared by EPD shows promising potential for subperiosteal TAD applications, promoting rapid osseointegration at the bone–implant interface[40].

ZnO NPs induce bacterial cell death by deactivating respiratory chain enzymes and increasing reactive oxygen species (ROS) production. A recent in vitro study demonstrated that orthodontic miniscrews (OMSs) coated with ZnO NPs exhibited greater antibacterial activity than those coated with Ag/HA NPs[36]. Furthermore, ZnO NP-coated OMSs displayed lower cytotoxicity and enhanced cytocompatibility compared to Ag/HA NP-coated counterparts, as evidenced by in vitro tests on fibroblasts, osteocytes, osteoblasts, and oral epithelial cells[36]. These findings suggest that ZnO NPs hold promise for minimising inflammation around OMSs[36].

Although titanium-based materials are frequently employed in TADs, they can cause excessive bone resorption and impede bone regeneration. Polyetheretherketone (PEEK) offers high biocompatibility with the human body, preventing allergic reactions to TADs and reducing the pressure-holding effect, and thus serves as a valuable alternative TAD material. Molecular docking investigations revealed that the docking of PEEK and HA exhibits a higher binding affinity for osteogenic markers related to osseointegration, such as insulin-like growth factor-1 (IGF-1) and alkaline phosphatase (ALP), rendering it a more suitable biomaterial for osseointegration than either PEEK or nano-HA alone; however, further in vitro, in vivo and clinical studies are required to examine the biological, chemical and mechanical properties of PEEK and HA combinations extensively[39].

A recent study demonstrated that, under controlled TAD design, loading protocols, and surgical and placement techniques, and accounting for random host factors, the survival rates and removal torque values (RTVs) of nanoporous surfaces (100.0%) surpassed those of microporous surfaces (83.3%)[38]. TiO_2 nanotubes can be fabricated on OMS surfaces through anodic oxidation in a fluoride-containing electrolyte at low voltage. The nanoporous surface structures enhance early osseointegration by facilitating protein adsorption, osteoblast adhesion and bone tissue healing[38]. This enhancement may be attributed to the greater TiO_2 thickness, which provides improved hydrophilicity, increased surface area, enhanced surface roughness and superior biomechanical stability. To validate the findings of this study, further histological, biological and clinical investigations are necessary[38].

In an in vivo pilot study, nanotube arrays embedded with recombinant human bone morphogenetic protein-2 (rhBMP-2) or ibuprofen were placed on rabbit tibiae[37]. Eight weeks post-implantation, the bone–implant contact (BIC) ratio of ibuprofen-loaded OMSs (71.6%) was significantly higher than that of conventional OMSs (44.3%). The results indicated that TiO_2 OMS surfaces with nanotube arrays can function as drug carriers and that ibuprofen-loaded nanotube arrays can promote osteointegration of OMSs[37]. In addition to drug-loaded nanotube arrays, nanoscale structures for precise and painless drug delivery offer substantial potential in orthodontic applications. In a separate study, microneedle patches were employed to monitor bacterial growth by releasing specific, titrable antimicrobials or NPs that inhibited the proliferation of targeted bacteria[53].

Introduction of nanofillers or NPs to orthodontic adhesives

Bonding is the most prevalent technique for attaching brackets and bonds to teeth surfaces due to its simplicity and aesthetic appeal; however, orthodontic adhesives possess a greater retention capacity for cariogenic streptococci compared to bracket materials. White spot lesions, resulting from the accumulation of oral biofilm around orthodontic brackets and composite materials, are a common issue in orthodontic treatment, complicating oral hygiene maintenance for patients. Consequently, antimicrobial agents, such as fluoride, chlorhexidine and benzalkonium chloride, have been incorporated into orthodontic adhesives[27].

Nanocomposites have gained recognition as adhesives suitable for clinical use. The anticipated properties of nano-adhesives encompass high antimicrobial activity, biocompatibility, elevated translucency, superior polish, wear resistance and the elimination of the need for separate etching[54]. In comparison to traditional orthodontic adhesives, the integration of nanofillers contributes to reduced surface roughness, enhanced long-term optical properties and improved mechanical properties, such as compressive and tensile strength, due to the high surface–volume ratio of nanofillers[10]. A nano-scratch experiment conducted on enamel demonstrated that nanocomposite adhesives and conventional adhesives exhibited similar tribological behaviours (including wear resistance, scratch hardness and friction coefficient). Given its impact on enamel following bracket removal, as well as its mechanical and physical characteristics and bond strength, nanocomposite adhesive emerged as the preferred choice for bonding orthodontic brackets[55].

However, in vitro experiments revealed that the shear bond strength (SBS) decreased following the incorporation of AgNPs (0.3% (w/w)), though it remained acceptable (exceeding the clinically recommended bond strength of 5.9 to 7.8 MPa)[29]. The studies encompassed in this systematic review and meta-analysis confirmed that orthodontic adhesives containing AgNPs exhibited significant antibacterial activity. Nonetheless, due to the lack of standardised protocols in the in vitro models, a degree of heterogeneity was present between the studies. The long-term efficacy of orthodontic adhesives with incorporated AgNPs in a simulated oral environment warrants further investigation[56].

Studies have suggested that varying concentrations of chitosan NPs (CNPs) exhibit different antibacterial effects against the multispecies biofilm of cariogenic bacteria on orthodontic primer in a rat model. Orthodontic primers incorporating 10% CNPs maximally inhibited *S. mutans*, *S. sanguinis* and *L. acidophilus* for up to 7 days. Given the competition between *S. mutans* and *S. sanguinis* in the oral cavity, the presence of the latter can reduce the count of *S. mutans*. Results demonstrated that orthodontic primers containing a 5% concentration of CNPs exerted a non-selective inhibitory effect against *S. mutans* and *S. sanguinis*; however, as the CNP concentration increased from 1% to 10%, the SBS experienced an insignificant decrease[28].

Incorporating a 1.3% mass fraction of zinc oxide NPs or 3% cinnamon NPs into orthodontic adhesives has been demonstrated to enhance their antibacterial properties and hinder biofilm formation without compromising the adhesives' properties or SBS[26,27]. Moreover, this modification reduced the development of caries lesions around brackets during orthodontic treatment. As nano-zinc oxide and nano-chitosan particles have both exhibited antibacterial properties, a novel study sought to combine them in varying proportions to capitalise on their synergistic benefits[57]. In vitro experimental findings revealed that incorporating

1% and 5% zinc oxide and chitosan particles did not adversely affect the SBS of adhesives[57].

Fluoride, a dual-functional anti–caries lesion agent, has been utilised in resin-modified glass ionomer cements, although its concentration of released fluoride is insufficient for long-term suppression of biofilm metabolism. For the first time, 20 wt% NPs of calcium fluoride (nCaF_2) and 3 wt% dimethylamino hexadecyl methacrylate (DMAHDM) were integrated into orthodontic cement. The results indicated that the innovative orthodontic cement increased enamel hardness by 56%, decreased lesion depth by 43%, reduced biofilm CFU by 3log and significantly diminished metabolic activity, polysaccharide production and acid production. Assuming no adverse effects on bracket-enamel SBS and biocompatibility, the novel nanostructured orthodontic cement possesses superior antimicrobial and remineralisation capabilities compared to commercial orthodontic cement, potentially decreasing the incidence of enamel demineralisation, white spot lesions and caries lesions during orthodontic treatment[25].

Recent research has focused on the development of novel remineralisation techniques as alternatives to fluoride. Upon using nano-hydroxyapatite on demineralised enamel, researchers observed higher SBS values than in untreated samples, albeit still lower than those in normal enamel[23]. Furthermore, the microhardness values increased to 278.97 VHN following remineralisation treatment, compared to 238.76 VHN for demineralised enamel. Based on these findings, employing biomimetic nano-hydroxyapatite on demineralised enamel surfaces during orthodontic treatment is advisable within certain limitations; however, complete remineralisation treatment should be avoided prior to bonding to prevent a decrease in SBS[23]. Not only does nano-hydroxyapatite remineralise demineralised enamel, but it also enhances the mechanical properties of orthodontic adhesives when combined with a conventional Heliosit adhesive resin at specific concentrations. A conventional Heliosit/Ivoclar Vivadent adhesive containing 2% wt calcium hydroxyapatite NPs demonstrated improvements in both the degree of conversion (DC) and SBS; however, incorporating 4% wt NPs led to a reduction in the DC and a decrease in the SBS of orthodontic adhesives. The primary cause of these reductions was the agglomeration of calcium hydroxyapatite NPs, which interfered with light penetration through the adhesive layer, resulting in a substantial decline in the photopolymerisation process[24].

Apart from the aforementioned nanofillers and their various combinations, numerous novel NPs can enhance the performance of orthodontic adhesives. Nano-graphene oxide (N-GO) is known to exhibit reduced toxicity, an improved surface–volume ratio, superior mechanical properties and cost-effectiveness. A study employed scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), X-ray diffraction (XRD) and Zeta potential analysis to confirm the successful synthesis of N-GO, and concluded that the incorporation of N-GO is beneficial for orthodontic adhesives[22]. SBS testing and the adhesive remnant index (ARI) were used to assess the physical-mechanical properties of N-GO-incorporated adhesives[22]. The results indicated that adhesives containing 5 wt% N-GO significantly enhanced SBS without negatively impacting the ARI. In the disk agar diffusion test, N-GO addition was found to impart antimicrobial and anti-biofilm properties against *S. mutans* to the adhesives; however, as the proportion of N-GO in the orthodontic adhesives increased, the mean SBS decreased despite a notable inhibition of *S. mutans* growth[22]. Clinical trials should be conducted to verify the anti-caries properties of N-GO-incorporated adhesives[22].

Removable orthodontic appliances with NPs

Removable orthodontic appliances, such as expanders, functional appliances and retainers, are frequently constructed from cold-cure acrylic resins[58]. These resins primarily consist of polymethyl methacrylate (PMMA)[59], a material favoured for its affordability, low weight and aesthetic appeal[60]; however, PMMA removable appliances are prone to surface porosities, which can harbour *Streptococcus spp.*, *Lactobacillus spp.*, *Enterobacteriaceae* and non-streptococci anaerobic bacteria. Patients who wear removable orthodontic devices tend to exhibit elevated levels of *C. albicans* in their saliva, increasing their risk of developing candidiasis and stomatitis. Furthermore, there is a direct correlation between removable orthodontic appliances and an increase in periodontal pathogenic microorganisms[61]. Although mechanical cleaning can help mitigate biofilm formation, it has proven to be largely ineffective in fully eliminating microorganisms, as they can infiltrate PMMA to depths of 1 to 2 mm. The efficacy of antibacterial solutions largely relies on patient compliance, which can be compromised among children, underscoring the need for greater focus on the self-sterilizing properties of PMMA. To imbue acrylic resins with bactericidal activity, NPs such as silver, platinum, titanium dioxide (TiO_2) and zinc oxide (ZnO) have been incorporated into the materials; however, the potential release of metal ions and their impact on the biocompatibility of acrylic appliances, as well as the resistance mechanisms of microorganisms, limit the long-term use of metal NPs[62].

In recent studies, nano-graphene and carbon nanotubes have been incorporated into polyurethane resins to enhance properties such as mechanical strength and thermal conductivity[63,64]. Given the successful application of propolis in preventing dental caries and gingivitis demonstrated in earlier studies, propolis NPs (PNPs) were introduced into PMMA. The findings indicate that a 1% concentration of PNPs potentially offers the most effective anti-biofilm performance for clinical use, exhibiting antimicrobial properties against *S. mutans*, *S. sanguinis*, *L. acidophilus* and *C. albicans*[60]. Aligners coated with quaternary ammonium (QA)-modified gold nanoclusters (QA-GNCs) can efficiently inhibit the adhesion of cariogenic pathogenic *S. mutans* and the formation of biofilm for at least 3 months[65].

Future applications of nanotechnology in orthodontics

Shape memory polymers

Shape memory polymers (SMPs) are materials with the ability to recall macroscopic or equilibrium shapes. They can be manipulated and set to temporary or dormant shapes under specific temperatures and pressures and can revert to their original shape upon suitable stimulation, such as heat, electric and magnetic fields, water, light or physiological triggers (pH, body temperature, specific ions or enzymes)[33]. Advantages like simple installation, effortless shape adjustment, light weight, comfort and aesthetic appeal render SMPs a promising material for use in orthodontics[32]. Incorporating graphene NPs and carbon nanotubes into SMPs can boost their mechanical properties and thermal conductivity[30,31]. Nanotechnology-modified SMPs can deliver light and continuous force for extended periods, alleviate patient discomfort and maintain an aesthetically pleasing appearance.

Biological nanoelectromechanical systems

A significant issue in orthodontics is the extended treatment duration. Research on animals has demonstrated that electricity can effectively expedite tooth movement, elevate cAMP and cGMP concentrations in osteoblasts and periodontal ligament cells, and hasten the synthesis and secretion associated with bone remodelling. Microfabricated biocatalytic fuel cells can generate electricity in the oral environment to facilitate orthodontic tooth movement. Using glucose as a fuel source and immobilising enzymes on electrode surfaces for electricity production presents challenges, such as limited lifespan and suboptimal power density. A range of nanostructured materials, including mesoporous media, NPs, nanofibres and nanotubes, have been identified as efficient hosts for enzyme immobilisation. Integrating these nanostructured conductive materials can enhance the activity and stability of immobilised enzymes and improve the power density of biofuel cells[34,35].

Orthodontic nanorobots

Nanorobotics is the field of designing and constructing nanorobots, which consist of components at or near the nanometre scale. Nanorobots can expedite tooth movement using NEMs and nano low-intensity pulsed ultrasound devices. Furthermore, integrated nanomechanical sensors enable clinicians to apply force precisely. Nanorobots can be administered through mouthrinse or toothpaste, providing continuous calculus debridement and safe self-inactivation upon ingestion. Additionally, nanosensors have been examined and validated for remote, objective monitoring of wear and adherence to orthodontic removable appliances[66].

Conclusion

In recent years, nanotechnology has impacted the field of stomatology significantly, leading to substantial innovation and benefits. Numerous dental nanomaterials have emerged and demonstrated immense potential in orthodontics, particularly in enhancing the mechanical and antimicrobial properties of orthodontic appliances. The integration of constantly evolving nanotechnology into clinical orthodontic treatments still draws attention. Although nanotechnology undoubtedly offers advantages in making orthodontic treatment more comfortable, rapid, straightforward and aesthetically pleasing, cytotoxicity and biocompatibility must be considered carefully when introducing new nanomaterials. The oral environment is dynamic, and the nanoscale size of NPs could potentially disrupt biomolecules, cells and human organs, or even induce oxidative stress that impairs human cellular mitochondrial function. The potential toxicity of nanomaterials is not yet fully understood; thus, further investigation is necessary to gather information on the long-term in vivo performance and safety of nanomaterials in orthodontics. Besides ensuring human safety, the environmental impact of nanomaterials should also be addressed. Future research should focus on controlling the release of nanomaterials in a targeted and quantitative manner, thereby maximising their efficacy and safety in the context of nanotechnology applications.

Conflicts of interest

The authors declare no conflicts of interest related to this study.

Author contribution

Dr Yi Lin WANG contributed to drafting the manuscript; Dr Zhi Jian LIU contributed to supervision and revision of the manuscript. All authors contributed to the article and approved the submitted version.

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