



REVIEW ARTICLE

The implications and applications of nanotechnology in dentistry: A review



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Abstract The emerging science of nanotechnology, especially within the dental and medical fields, sparked a research interest in their potential applications and benefits in comparison to conventional materials used. Therefore, a better understanding of the science behind nanotechnology is essential to appreciate how these materials can be utilised in our daily practice. The present paper will help the reader understand nanoscience, and the benefits and limitations of nanotechnology by addressing its ethical, social, and health implications. Additionally, nano-applications in dental diagnostics, dental prevention, and in dental materials will be addressed, with examples of commercially available products and evidence on their clinical performance.

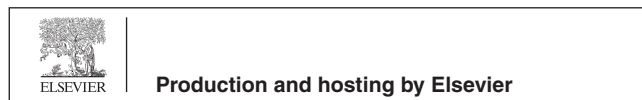
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1. Introduction

Nanotechnology is the art and science of material engineering in a scale of less than 100 nm (Anisa et al., 2003). It revolutionized the medical and dental fields by improving mechanical and physical properties of materials, helped introduce new diagnostic modalities and nano-delivery systems (Kanaparthi and Kanaparthi, 2011).

The first guidelines developed in the field of nanotechnology were by K Eric Drexler from the foresight institute. He presented the science of nanotechnology to the public through his published book *Engines of Creation* (Anisa et al., 2003). In an effort to create an eco-friendly socially acceptable nanotechnology, the United States National Human Genome Research Institute proposed a new approach to the development process of new technology. This was accomplished by addressing the ethical, legal, and social implications before nano-products reach the market to easily modify and adjust during the early stages of production (Ramsay, 2001; Macnaghten et al., 2005).

The ongoing research in the realm of nano, is due to the unique properties nanoparticles offer. Atoms are the building blocks in biological tissue, and these atoms are measured using the nanoscale. Introducing nano-sized particles allows for an interaction on a molecular level, by that increasing the overall efficacy and affinity in comparison to biological molecules interacting with micro or macro sized particles (Li et al., 2008). The high surface to core ratio, is a unique physical characteristic in nanoparticles, meaning that there are more atoms on the surface of the nanoparticle than deep within its core. This is particularly useful since surface atoms have unbound surfaces in comparison to core atoms, with the potential for creating new and strong bonds, and hence, nanoparticles are more reactive in comparison to micro and macro particles which have more core than surface atoms (Binns, 2010).

In comparison to the same material in bulk (macro or micro), nano particles can be easily arranged in a number of packing configurations due to their high surface to core ratio, making them easily manipulated and utilised in various applications. The greater thermal vibrations expressed by surface atoms in comparison to core atoms in any given material regardless of particle size, contribute to the lower melting temperature in nanomaterials compared to the same material in bulk (Buffat and Borel, 1976). This might be of particular importance when using nanomaterials to construct porcelain fused to metal (PFM) crowns, cast post and cores, or denture frameworks.

Many authors published review articles discussing the potential of nanotechnology in dentistry including newly developed materials, however, the literature is void of reviews

addressing the science behind nanotechnology in detail and linking it to the implications and applications of nanotechnology on the field of dental sciences (Mitra et al., 2003; Raval et al., 2016). This review addresses the science, implications, and up-to-date applications of nanotechnology in dentistry, including commercially available newly developed materials and supporting literature to aid dentists in understanding the clinical relevance and effectiveness of such materials in comparison to the ones currently used in clinical practice.

2. Implications of nanotechnology

2.1. Ethical implications

After the research and development phase of any dental or medical nanoproduct, it undergoes extensive preclinical *in vitro* testing to investigate its mechanical, toxicological, and immunological properties. Many agencies such as the U. S Environmental Protection Agency and the National Institute of Occupational Safety and Health have introduced guidelines for investigating the risks of nanomaterials (Resnik and Tinkle, 2007). However, developing a multidisciplinary regulatory framework to assess and control nanotechnology and resolve ethical concerns that fall under the four categories: metaphysical, equity, privacy, and security is a constant legislative challenge (Hester et al., 2015). Although animal studies provide a reasonable understanding of what to expect when starting a phase I trial, serious adverse reactions have been recorded when human subjects were exposed to a dose of nanomedicine 500 times less than the recorded toxic limit in animal studies (Resnik and Tinkle, 2007). Therefore, subjects must understand the level of risk associated with the exposure to novel materials and data and safety monitoring boards must be appointed in every clinical trial, to carefully track and record any adverse side effects early on, pick up inconsistencies in data handling, and insure the safety and wellbeing of test subjects (Resnik and Tinkle, 2007). The unpredictability of nanomaterials create an ethical dilemma for dentists when faced with a wide range of materials to choose from, some having very long track records supporting their clinical use such as hybrid or micro filled composite resins and others such as the nanofilled composite resins that are appealing in concept and supported by short term clinical studies. The traditional ethical decision making process followed, mainly utilitarianism, is unable to keep up with the rapid pace and uncertain future of nano-technological developments. For that reason, a more in depth understanding of the science is required, including risk/benefit analysis and ethical considerations throughout the development process. This lead to the proposal of the anticipatory ethics and governance concept, developed to

identify and address ethical and societal implications through ethical analysis models when the technology is in its introductory stage to be then easily modified and guided towards an ethically acceptable outcome (Hester et al., 2015; Brey, 2012; Khushf, 2006).

2.2. Nanotechnology and society

Since society is the consumer, funding party, and policy and decision maker, the public's attitude towards nanotechnology plays a fundamental role in its success and failure, in other words society is the judge and jury. This is driven by ethics, morals, and values that have recently become more accepting of the new sparking technologies as the perceived benefits outweigh the perceived risks (Gupta et al., 2015). However, although nanotechnology is currently integrated in fields that directly affect the public such as in energy supply, health care and diagnostics, telecommunications, and pollution control, this has created fear as these advancements might cost the public thousands of jobs to accommodate for a more machinery reliant system (Kurzweil, 2005). In an effort to address social concerns, various initiatives were put in place to bridge the gap between society and nanoscience. The National Nanotechnology Initiative report claims that advancement in technology will require a new generation of trained workers with advanced set of operational and managerial skills (Macnaghten et al., 2005). In 2003, Technologist Ray Kurzweil claimed that: "Portable manufacturing systems will be able to produce virtually any physical product from information for pennies a pound, thereby providing for our physical needs at almost no cost" (Fisher and Mahajan, 2006). This calls for an immediate engagement with the public to address concerns and spread awareness on current and future applications of nanotechnology to gain and maintain public support.

2.3. Health implications

A four stage framework has been adopted by the US federal and state agencies to assess and evaluate the magnitude of any health concern, starting with problem identification, followed by dose-response assessment, exposure assessment, and ending with risk characterization (Stander and Theodore, 2011). The effects of nanomaterials are significantly size dependant, meaning that nontoxic 100 nm sized particles could dramatically transform into toxic elements as their size reduce to 1 nm for example and vice versa. A non-toxic nanomaterial could disintegrate or aggregate forming toxic nanoparticles as well. This unpredictability of how our bodies react to nanomaterials not only relies on size but in how our immune system react to the nanoparticle, as studies have shown that nanoparticles could react differently in a cell culture than in an organism.

Studies have shown that nanoparticles can be inhaled and can cross cell membranes and reach the liver, lymph nodes, spleen, and bone marrow (Resnik and Tinkle, 2007). Although claims of nano-toxic effects following inhalation have been clearly expressed, the literature lacks solid scientific evidence confirming or denying these claims (Stone et al., 2010). Therefore, although private companies are not required to perform post marketing studies on their products, governmental bodies must sponsor and encourage such studies to investigate the

long term effects of nanomaterials and report any adverse side effects to legislative and regulatory bodies such as the U.S. food and drug administration (FDA). Studies on ethical, social, and health implications of nanotechnology fall far behind the science, and regardless of funding availability, serious attempts to consider the issues at hand fail to exist, instead hype pieces and controversies which only add to the public confusion and mistrust of disrupting new technologies exist, or as referred to by Bill Joy "grey goo" (Joy, 2000).

3. Applications of nanotechnology in dentistry

3.1. Dental diagnostics

In an attempt to improve upon medical diagnostics, the concept of nano-biosensing was introduced. A biosensor is "an analytical device which incorporates a biologically active element with an appropriate physical transducer to generate a measurable signal proportional to the concentration of chemical species in any type of sample" (Touhami, 2014). Biosensors were introduced in 1962 by Clark and Lyons (1962), followed by an ongoing extensive research and development of this promising technology by utilising various detection principles, leading to potential applications in public health, environmental monitoring, and food safety (Table 1) (Touhami, 2014). In an effort to improve the biorecognition process and overall bioreceptor performance, nanobioreceptors were introduced, incorporating nanotubes, nanowires, and nano-dots in the sensing assembly (Sagadevan and Periasamy, 2014).

Nanoparticles are created by either following the top down, bottom up, or molecular self-assembly approach (Foster, 2005). Replacing micro sized particles with nanosized ones transforms the biosensor into a nanobiosensor, with the advantage of rapidly identifying targeted biological tissues at an ultra-low molecular level. Its high sensitivity is particularly useful in cases of cancer diagnosis for example, as nanobiosensors in comparison to conventional biosensors are able to

Table 1 Detection principles in nano-biosensors.

Detection Principle	Definition
Piezoelectric	Piezoelectric biosensors have the ability to generate an electrical charge in response to mechanical stress, and the translation of mechanical energy to electrical energy is called the piezoelectric effect (Kumar, 2000)
Electrochemical	This detection principle starts with the analyte (target) chemically binding to the highly specific bioreceptor (e.g. a fixed enzyme), affecting the electronic properties of the sensor, and ultimately generating a readable signal (Hasanzadeh and Shadjou, 2016)
Optical	Optical nanosensors give quantitative measurements on an intracellular level. It converts the biorecognition of the analyte into an optical signal (Clark et al., 1999)
Calorimetric	Thermal biosensors or calorimetric biosensors rely on the rate of enzymatic exothermic reaction to measure the concentration of the analyte

detect cancer cell molecules at very early stages and in very low concentrations (Touhami, 2014; Foster, 2005). Nanobiosensors are also mechanically compliant, as they are easily displaced and deformed in response to very low forces, therefore, sensitive enough to detect breaking of chemical bonds (Arlett et al., 2011). This is attributed to its nano size effects, as the high surface area to core ratio increases the level of sensitivity, electrical properties, and response time of the biosensor (Sagadevan and Periasamy, 2014).

Metallic nanoparticles such as gold, silver, platinum, and palladium are commonly incorporated in nanobiosensor transduction/bioreception systems as they are able to rapidly react with most biological molecules without affecting their activity (Sagadevan and Periasamy, 2014). Gold nanoparticles have been deeply studied, revealing an ability to enhance the electronic signal when the bioreceptor detects the analyte at very low concentrations, for example, gold nanoparticle modified DNA bioreceptor detects an analyte at a concentration as low as 0.05 nM (Su et al., 2003).

Additionally, carbon nanotubes were utilised for the detection of circulating cancer cells in the body. The carbon nanotubes were arranged by the layer-by-layer assembly technique and then linked chemically to antibodies of specific carcinogenic marker which specifically binds to cancer cells, thus, providing an effective and useful diagnostic tool (Hasanzadeh and Shadjou, 2016).

This not only enhances the performance of biosensors, it also creates an opportunity to manufacture very small sizes of nanobiosensors that can be worn or even implanted as opposed to larger sizes of conventional biosensors that are not feasible and cost more to manufacture (Touhami, 2014).

3.2. Preventive dentistry

Researchers developed a nano-toothbrush, by incorporating nanogold or nanosilver colloidal particles between toothbrush bristles (Raval et al., 2016). In addition to its ability to improve upon mechanical plaque removal, researchers reported an antibacterial effect of the added gold or silver which could ultimately lead to a significant reduction in periodontal disease.

Oral hygiene products such as toothpastes and mouthwash solutions were also nano-modified according to recent reports. Nano-calcium fluoride, for instance, was added to mouthwash products to reduce caries activity, reduce dentine permeability, and increase labile fluoride concentration in oral fluid (Sun and Chow, 2008). Toothpastes containing calcium carbonate nanoparticles and 3% nanosized sodium trimetaphosphate have been reported to promote remineralisation of early carious lesions in comparison to a conventional toothpaste with no nano-additives (Danelon et al., 2015).

According to results from an *in vitro* study, toothpastes containing nano-hydroxyapatite crystals (nHA) significantly increased microhardness values in human enamel following an erosive challenge, in comparison to the same toothpaste without nHA (Ebadifar et al., 2017).

The benefits of a nHA containing toothpaste was first reported in Japan in the 1980s (Kani et al., 1989). In 1983, three primary schools were enrolled in their 3-year clinical study. Schools were provided with toothbrushes and toothpastes. One school was given a 5% nHA based toothpaste, while the other two schools were provided with controls.

Students were instructed to brush using the provided toothbrush and toothpaste every day during school hours and under a teacher's supervision. Results gathered revealed a 56% reduction in caries incidence in school children brushing with a nHA toothpaste in comparison to the control groups (Kani et al., 1989).

The higher reparative capacity of nanomaterials in comparison to the same material in a micro or macro scale, might be attributed to the fact that the inorganic building blocks in enamel are 20–40 nm in size, making it logical to assume a higher affinity to nanosized particles (Robinson et al., 2004; Tao et al., 2007). This is important to consider when attempting to develop new materials to improve mechanical, physical, and reparative characteristics.

3.3. Dental materials

3.3.1. Prosthodontics

Incorporating 0.4% TiO₂ nanoparticles into a 3D printed poly-methylmethacrylate (PMMA) denture base was investigated in 2017, in an attempt to improve its antibacterial characteristics and mechanical properties (Totu et al., 2017). According to measurements using Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy, and tests for antimicrobial efficacy against *Candida* species, improvements in the chemical and structural properties was reported, and the antibacterial effects specifically against *Candida* species was significant.

Researchers also investigated the tribological behaviour of a 7 wt% nano-zirconium oxide modified heat cured PMMA (Ahmed and Ebrahim, 2014). The addition of zirconium oxide nanoparticles significantly improved hardness levels, flexural strength, and fracture toughness of the heat cured PMMA denture base. Nano sized fillers were used due to their superior dispersion properties, less aggregation potential, and biocompatibility with the organic polymer. Nano zirconium not only improved physical properties of denture bases during the construction phase, they were reported to improve the transverse strength of a repaired denture base as well (Gad et al., 2016). Results show that repairs using an autopolymerised resin, modified with 2% or 5 wt% zirconium oxide exhibited the highest transverse strength levels using a three-point bending test. Researchers concluded that the incorporation of nano-modified zirconium oxide particles in resins matrices has a wide potential not only in removable prosthodontics but in many other disciplines as well.

Researchers additionally investigated the antifungal properties of a chlorhexidine coating with a range of nanoparticle additives, to inhibit fungal infestations in dental silicones commonly used as denture soft liners and obturators (Garner et al., 2015). Solutions of chlorhexidine mixed with sodium triphosphate (TP), trimetaphosphate (TMP) or hexametaphosphate (HMP) nanoparticles were used.

The addition of nanoparticles did not affect the hydrophilicity and water uptake of denture silicones following immersion in artificial saliva for 16 weeks. Furthermore, the nano-modified chlorhexidine coatings released soluble chlorhexidine into artificial saliva, with a slow and sustained release by the chlorhexidine-HMP coating, and a rapid, more concentrated release by the chlorhexidine-TP and chlorhexidine-TMP coatings. The chlorhexidine-HMP coating

proved to be the most effective in its antifungal activity by inhibiting the metabolic activity of *Candida albicans*. These coatings might potentially become clinically essential for insuring longevity of the dental prosthesis and maintenance of oral health at a much lower cost.

Nano-particle impregnated luting cements proved to be significantly effective in increasing the bond strength to enamel and dentine in comparison to conventional luting cements. They bond particularly well to dentin, as these very small sized particles penetrate deeper into the dentinal tubules, therefore, increasing the elastic modulus, and reducing polymerization shrinkage (Sadat-Shojai et al., 2010). Researchers in 2011 created a novel approach to improve compressive and tensile strength of zinc poly carboxylate, by incorporating ZnO and MgO nanoparticles. Results revealed excellent physical and mechanical strength when compared to conventional zinc poly carboxylate cements (Zebarjad, 2011). Researchers concluded that strength of cements depend on composition size scale, clearly evident through the significant differences observed between a nanomodified and a conventional zinc poly carboxylate cement in this study. Similarly, the addition of nano-hydroxyapatite/fluoroapatite particles to glass ionomer cements, significant increased the compressive, tensile, and biaxial flexural strength in comparison to conventional glass ionomer cements (Moshaverinia et al., 2008; Lucas et al., 2003).

Tribological improvements were also observed in the newly introduced resin nano-ceramic computer-aided design and computer-aided manufacturing (CAD/CAM) blocks. The Lava™ ultimate resin nano ceramic blocks manufactured by 3 M™ ESPE, showed superior aesthetics, durability, and fracture resistance (Chen et al., 2014). Blocks are made of a nano-ceramic impregnated highly cured resin matrix, which can be easily modified and customized after milling (Koller et al., 2012). The nano-ceramics and resin hybrid created materials with superior properties as compared to when using one or the other.

Although some nanoparticles prove advantageous, researchers are required to insure safety in using such materials in everyday clinical practice, by addressing their long term biocompatibility, toxicity, mechanical, and physical properties.

3.3.2. Endodontics

Applications of nanotechnology in endodontics include the incorporation of bio-ceramic nanoparticles such as bioglass, zirconia, and glass ceramics in endodontic sealers. It has been found that the use of nano-particles enhances the adaptation of the adhesive to nano-irregularities, in addition to its fast setting time in comparison to conventional sealers, its dimensional stability, insolubility in tissue fluid, chemical bond to tooth tissue, and osseointegration (Utneja et al., 2015). This was corroborated by a recent study, testing the antibacterial effects against endodontic biofilm, bond strength to dentine, and the ionic release of calcium and phosphate when a novel bioactive endodontic sealer was used (Wang et al., 2017). The sealer was a mix of dimethylaminohexadecyl methacrylate (DMAHDM), 2-methacryloyloxyethyl phosphorylcholine (MPC), and amorphous calcium phosphate nanoparticles (NACP). The sealer was able to inhibit the formation of endodontic strains, while the nano-particles were particularly useful in accelerating the remineralization process and in increasing bonding strength to dentine.

In an effort to improve upon intracanal medicaments in inhibiting the growth of *Enterococcus faecalis*, the short term and long term effects of calcium hydroxide intracanal medication with silver nanoparticles suspension was investigated (Afkhani et al., 2015). Its effectiveness against *Enterococcus faecalis* was superior when compared to calcium hydroxide alone, and calcium hydroxide mixed with chlorhexidine. Nano-silver particles were significantly effective after one week, and showing no significant antibacterial effect after one month in comparison to the other materials used. Researchers, therefore, concluded that nanosilver particles proved to be an effective antibacterial agent specifically against *Enterococcus faecalis* in short term. An *In-vitro* study conducted in 2014, concluded that nanosilver particles were not efficient in inhibiting *Enterococcus faecalis* after one week (Mozayeni et al., 2014). Nano-silver particles were introduced into a gel matrix and applied as a root canal sealer. This nano-silver gel proved to be less efficient than chlorhexidine and triple antibiotic paste in inhibiting the spread of *Enterococcus faecalis*. Researchers attributed the lack of efficiency exhibited by the nanosilver gel to its synthesis method which was different than that of chlorhexidine and triple antibiotic paste, in addition to the gel consistency, which might have inhibited the release of nanoparticles.

Studies were additionally conducted to improve upon gutta percha (GP), by incorporating nano-diamond particles (Lee et al., 2015). Digital radiography and micro-computed tomography imaging revealed that obturation following a conventional technique, using nanodiamond impregnated GP, demonstrated superior chemical properties, biocompatibility, and superior mechanical properties. Additionally, high quality adaptation to the canal walls and minimum void formation was reported, which demonstrates the great potential for the use of nano-GP as an improved endodontic filling.

3.3.3. Conservative and aesthetic dentistry

The new development of a rechargeable nano-amorphous calcium phosphate (nACP) filled composite resin has been recently reported. The nanoparticles were able to not only improve composites' remineralising properties, it also maintained the same level of Ca and P release through recharge and release (Xie et al., 2016). Researchers described it as a "smart" material through its constant ability to rapidly neutralise bacterial acids released along the restoration/tooth margins through the release of Ca and P, therefore was able to inhibit the initiation of secondary caries. This was corroborated by Wu et al., reporting a significant remineralising ability of nACP and its effectiveness in inhibiting the initiation of secondary caries (Wu et al., 2015). Researchers also reported that their results create a possibility for integrating nACP in other dental materials such as luting cements and bonding agents. This was corroborated by another study, showing a significant remineralising ability in a dental bonding agent with nACP through the recharge and release of Ca and P ions for up to 3 week, without altering the bonding strength to dentine (Zhang et al., 2015).

An additional attempt to enable restorative materials to actively prevent the initiation and progression of secondary caries, was through the application of a nanocomposite coating consisting of lactose-modified chitosan (Chitlac) with silver nanoparticles (nAg) (Ionescu et al., 2015). Nanoparticles were

evenly dispersed and were able to significantly reduce biofilm formation on the restoration surface by 80% after 48 h of application, in comparison to a control with no Chitlac-nAg coating. Images obtained by Confocal Laser Scanning Microscopy (CLSM) revealed that the coating had no bactericidal activity, however, it had the ability to alter the biofilm morphology, and by that inhibiting the development of mature biofilm species.

Incorporating cross-linked quaternised polyethyleneimine (QPEI) nanoparticles in resin composites was also reported to have antibacterial effects against various oral pathogens, such as *Enterococcus faecalis*, *Streptococcus mutans*, *Actinomyces viscosus*, *Lactobacillus casei*, and whole saliva. The addition of QPEI nanoparticles were reported to have a long lasting antibacterial effect, stable within the matrix, and did not leach out into the surrounding environment (Shvero et al., 2015). The addition of QPEI nanoparticles caused the disruption of ionic exchange through bacterial membranes within the biofilm, and therefore, leading to cell death. Its bactericidal properties might create a second generation of restorative materials with significantly lower incidences of failure by secondary caries.

Tooth whitening agents were additionally nano-modified to increase their whitening efficiency and minimise their harmful side effects. Calcium peroxide nanoparticles, for instance, were able to penetrate deeper into the tooth structure through micro and nano cracks, leading to a longer surface contact and therefore an increase in the effectiveness of the whitening agent as its deeper penetration into the tooth structure allows for a longer action time and ultimately a significant improvement in aesthetics when compared to a whitening agent with micro or macro particles (Velkoborsky, 2010). Additionally, the incorporation of nano-lipobelle H-EQ10 into the whitening agent significantly improved the chemical and mechanical condition of whitened enamel. Nano-lipobelle H-EQ10 are liposomes loaded with 10% vitamin E and 5% coenzyme. The use of nano-liposome carriers enables the delivery of higher quantities of vitamin E and coenzymes which aid in the protection of tooth structure and the stimulation of cell regeneration respectively (Velkoborsky, 2010).

3.3.4. Periodontics, Implantology, and regenerative dentistry

Scientists were able to create a novel drug delivery system for the treatment of periodontal disease, through triclosan or tetracycline loaded nanoparticles.

These nanoparticles are uniformly dispersed within a matrix, which gradually biodegrades, releasing loaded drugs in increments to provide a longer contact duration with the diseased site (Sharma et al., 2016). Niosomes, for instance, are chemically stable non-ionic vesicles, which offer a controlled and targeted drug delivery with enhanced penetration through biological tissue especially when the particles are less than 100 nm in size (Pradeepkumar et al., 2012). Furthermore, fullerenes have been heavily studied for their many potential applications, one of which is its effectiveness in drug delivery. Fullerenes are hollow carbon molecules which come in different shapes (spheres, tubes, and ellipsoids). The buckminsterfullerene (C₆₀) was the first and most stable fullerene discovered in the 1980s, which resembled the geodesic domes designed by Buckminster Fuller, hence, named after him. These fullerenes can be constructed by either a bottom up

approach, building it atom by atom, or by a top down approach from larger atoms, which according to the literature proved to produce a more stable fullerene structure (Andreoni, 2000). It was additionally used for other purposes in the medical field, such as radical scavenging and as antioxidants.

The literature also reports the benefits of combining a light curable, methacrylate resin matrix, with nACP as a bone grafting agent. This injectable material has the ability to strongly adhere to wet bone, and in recrystallizing nACP to hydroxyapatite in a matter of minutes (Pradeepkumar et al., 2012).

It has been theorised that the osseointegration of implants within the jaw bone would be maximised if the implant surface was mimicking the surface topography of the extracellular matrix within natural tissue, which is typically between 10 and 100 nm in size (Tomsia et al., 2011). Published data proved this theory, as not only surface coatings such as hydroxyapatite, gold, silver, and titanium oxide nanoparticles have the ability to improve the adhesion of the fibrin clot which serves as a bridge for osteogenic cells and the overall osseointegration of implants, the presence of mechanical nano-features such as nano-grooves or nano pillars have been proved effective as well, with particular emphasis on the distribution and order of such features on the implant surface (Tomsia et al., 2011; Cheng et al., 2012; Besinis et al., 2017).

4. Nano-products

Various range of nano-additives have been introduced into many commercially available products, making it overwhelmingly difficult for dentists to choose from. Commonly used commercially available nanomaterials, and studies on their nano-additives in Table 2 will shed some light on the effectiveness of such nanomaterials in comparison to their conventional counterparts.

5. Conclusion

The science and applications of nanotechnology are constantly evolving as we witness new products being introduced into the market. This comes with great responsibility to insure the safety, efficiency, and applicability of such new technologies. Their level of effectiveness as shown in the literature diverge, being more effective than some materials and less effective than others. Although nanomaterials generally offer superior aesthetics and polishability, their mechanical properties fall short in comparison to microfilled resin composites for example. Therefore, the choice to use nanomaterials is dependent on the clinical scenario and tooth to be restored, paying close attention to aesthetic demand, loading, and the presence of any risk factors such as parafunctional habits. Research to improve upon existing nanomaterials is still ongoing, with future directions towards more efficient and cost effective nano-biosensing devices to diagnose in high accuracy oral cancer for example, in addition to new oral drug delivery systems to disrupt biofilm formation and reduce the incidence of caries and periodontal disease. Although the science behind nanotechnology is intriguing, the lack of long term clinical evidence addressing their clinical performance restricts their wide clinical use.

Table 2 Commonly used commercially available nanomaterials.

Discipline	Classification	Material	Brand	Nanoparticles	Literature	
Prosthodontics	Denture teeth	Nano-hybrid composite	NHC SR Phonares®; Ivoclar Vivadent	Silicon oxide	– Significantly higher wear in comparison to interpenetrating polymer network (IPN) and double crosslinking polymethylmethacrylate (PMMA) denture teeth (Munshi et al., 2015)	
			Veracia (Shofu, Kyoto, Japan)	Spherical pre-polymerised silica	– Superior to conventionally used composites and acrylics in regards to hardness, smoothness, and stain resistance. However, its hardness was less than microfilled and double crosslinked acrylics. (Kumar and Seshan, 2014)	
Conservative	Restorations	Nano-Resin modified GIC	Ketac™ Nano 3M ESPE	Zirconia/silica nanofillers & nanoclusters	– Higher shear bond strength to enamel compared to GIC, and glass carbomer. (Shebl et al., 2015)	
			Nano-Composite Resins	Herculite XR Ultra, Kerr Tetric Evo ceram, IvoclarVivadent	Nanosilica SO ₂ spherical nanofillers	– Comparable fluoride release to conventional RMGIC (Paschoal et al., 2011)
		Nano-GIC	Filtek Supreme (3M)	– Non-aggregated 20 nm silica filler, – Non- aggregated 4 to 11 nm zirconia filler. – Aggregated zirconia/silica cluster filler (20 nm silica and 4 to 11 nm zirconia).	– Both materials exhibited high gloss values in comparison to micro-hybrid composites.	– Nanocomposites were not mechanically superior to micro-hybrids (Flexural strength, flexural modulus, and compressive strength). (Khalid, 2012)
			Ceram.x® Mono™ and Ceram.x® Duo™. Dentsply	Organically modified nano sized ceramic fillers comprising polysiloxane backbone (10 nm)	– Lower compressive strength in comparison to hybrid composite resin (Moezzyzadeh, 2012)	– Superior diametral tensile strength, and flexural strength, and comparable compressive strength, wear volume, and polymerisation shrinkage to microfilled and microhybrid composites (Lu et al., 2006)
Cavity Disinfectant	Mineral solution	GCP Glass Fill™, GCP Dental.	NanoCare gold® DNT™	Spherical silver nanoparticles (48 nm)	– Comparable compressive strength in comparison to hybrid composite. (Hegde et al., 2011)	
					Carbomised fluorapatite/hydroxyapatite nano particles	– Ceramic nanoparticles produce restorations with high translucency and polish comparable to microfilled resins, and superior physical properties and wear resistance comparable to hybrid composites. (Mitra et al., 2003)
Endodontics	Sealer	Silicon based	GCP Glass Fill™, GCP Dental.	Carbomised fluorapatite/hydroxyapatite nano particles	– Lower hardness and bond strength to dentine than high viscosity GIC. (Olegário et al., 2015)	
			GuttaFlow™ Coltène-Whaledent	Nano-silver	– Lowest surface roughness values in comparison to GIC and RMGIC (Arslanoglu et al., 2015)	
					– Moderately anti-bacterial. – The aggregation of nanoparticles will possibly cause an interaction with the restorative material (Mackiewicz and Olczak-Kowalczyk, 2014)	
					– Comparable sealing ability to AH Plus (Patil et al., 2016)	
					– The sealing ability is double that of AH plus after 9 weeks (De-Deus et al., 2007)	

(continued on next page)

Table 2 (continued)

Discipline	Classification	Material	Brand	Nanoparticles	Literature
Periodontics	Grafts	Bone grafts	NanoBone®Artoss GmbH®	Nanocrystalline hydroxyapatite	– Comparable to BioOss® in its low cytotoxicity and good biocompatibility. It additionally exhibited superior MTT proliferation results (Liu et al., 2011) – Comparable clinical results in cases of two and three wall intra-bony defects to autogenous bone grafts. (Chitsazi et al., 2011)
			Ostims, Heraeus Kulzer, Hanau, Germany	Nanocrystalline hydroxyapatite	
Implantology	Nano-implant coating	–	NonoTite BIOMET 3i	Nano-hydroxyapatite (around 50% of total surface area)	– Clinically favorable osseointegration with minimum marginal bone loss (1.01 mm), however studies were not randomized, had no controls, and were followed up for only one year (Smeets et al., 2016)

Conflict of interest

The author has no conflict of interest to declare.

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