Chapter 9
Applications of Nano Materials in Dental Sciences and Scope in Future Practice

Mohammad Afazal and Saba Afreen

1 Introduction to Nanotechnology

Richard Feynman first proposed the idea of nanotechnology in his famous speech "There's Plenty of Room at the Bottom" [1]. It attempts to use molecular engineering to create nano machineries that can produce nano materials. Under "Definition of Nanotechnology," an early NNI document (National Science and Technology Council [NSTC], 2000) claimed that the ability to operate at the molecular level, atom by atom, to develop enormous structures with fundamentally new molecular organization is the essence of nanotechnology. The behavior of structural features in the range of 10^{-9} to 10^{-7} (1–100 nm) exhibits significant alterations when compared to the behavior of isolated molecules of approximately 1 nm (10^{-9}) or of bulk materials. We will be able to organize atoms in any way we like, thanks to nanotechnology, which will allow us to effectively and completely control the structure of matter [2, 3].

Nanomedicine is a brand-new area that has emerged as a result of developments in the applications of nanotechnology in medicine [4]. According to Robert A. Freitas Jr., who first proposed this idea in 1993, this notion entails using nanostructures and nanodevices to observe, manage, and treat the biological systems of the human body at the molecular level [5]. The pharmaceutical business, where many medications are hydrophobic in nature and only sparsely or weakly soluble in aqueous solutions, is one of the most straightforward applications of nanotechnology. Due to the enormous increase in surface area, shrinking a pharmaceutical down to the nanoparticle size range can enable more of the drug to go into the solution [6]. Dental treatments using designed nano materials can improve therapeutic and preventative outcomes.

M. Afazal (✉)
University Polytechnic, Jamia Millia Islamia Delhi, New Delhi 110025, India
e-mail: mafazal1@jmi.ac.in

S. Afreen
Indraprastha Dental College and Hospital, Sahibabad, Ghaziabad 201010, Uttar Pradesh, India

A. Chanda et al. (eds.), *Materials for Biomedical Simulation*, Materials Horizons: From Nature to Nanomaterials, https://doi.org/10.1007/978-981-99-5064-5_9

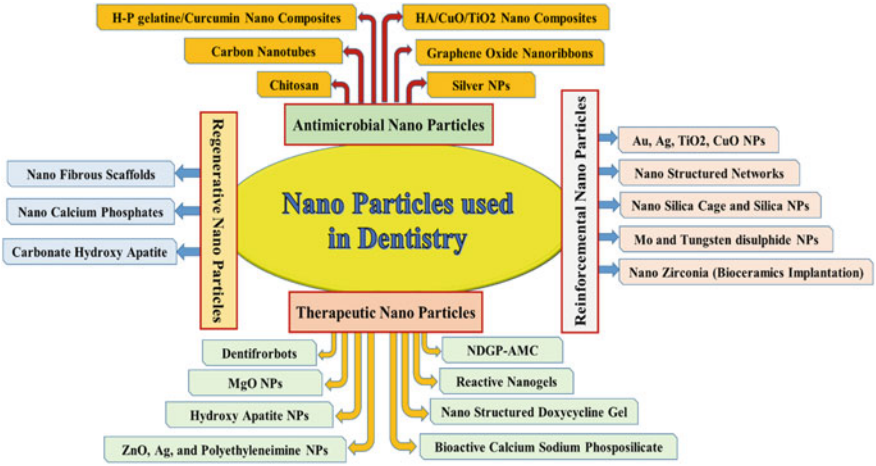

Fig. 1 Classes of nano materials used in dentistry

2 Nano Dentistry

The most recent advances in nanotechnology research and development can be used to improve and upgrade conventional dental materials and equipment. In order to create regenerative materials, nano fillers, nano composites, nano impression materials, target-oriented antimicrobial mouthwashes, implants, and drug-enclosing nanoparticles, various synthesis approaches, including bottom up, top down, functional, and biomimetic approaches, can be used in nano dentistry. A thorough grasp of the tooth's structure and environment, as well as expertise in the material, synthesis process, and synthesis technique, are necessary for the development of nano dental products. Since ancient times, dental biomaterials made of metals, ceramics, resins, and polymers have been created and further modified [7]. Polymers can be made from both synthetic and natural (plant- and animal-based) materials [8]. To improve the mechanical and optical properties of polymers, some uncommon materials, such as carbon nanotubes (CNT), graphene oxide, and nanodiamonds, can be used in place of traditional glass or carbon fibers [9] (Figs. 1 and 2).

3 Applications in Diagnosis

For the prevention or treatment of oral disorders caused by biofilms, a thorough understanding of bacterial adhesion—the primary factor in bacterial colonization and pathogenesis—as well as bacterial nano mechanics is necessary [10]. The ability of bacteria to cling to individuals of the same or other species as well as to various substrates, such as teeth and implants, has been well documented [11, 12]. AFM offers

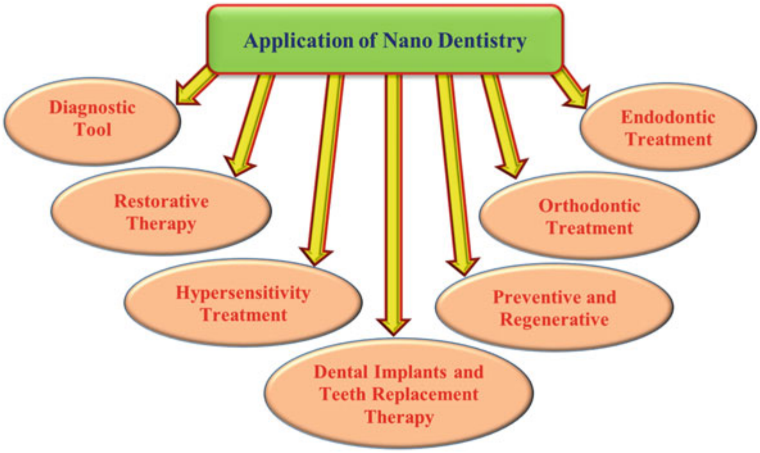

Fig. 2 Applications of nanoparticles in dentistry

a breakthrough in the characterization of bacteria as well as the measurement of their adhesion to various substrates [13, 14], because of its capacity to directly interact with imaging live cells without affecting their morphology and properties [15]. A real-time, highly sensitive scanning of a living bacterial cell was made possible with nanomechanical biosensors and an AFM cantilever [16]. Additionally, details on the characteristics of the membrane molecules [17] and the elasticity of a cell [18] are made available.

4 Application of Nano Dentistry in Conservative and Restorative Treatment of Teeth

The primary treatment needed in the oral cavity is caries management. To preserve the tooth's structural and cosmetic integrity, an appropriate restorative material has to be used to fill the tooth. After a tooth is lost, it is restored using a bridge, an implant, and a crown. Nanoparticles can be added to filling materials and implants to improve them. The material must be close to the tooth structure and adhere to it in order for the restoration of a carious tooth to be successful. Micro gaps, leaks, and ultimately filling failure are caused by compromised adhesion or intersurface integrity [19, 20]. For enhanced defense, mineral deposition, and sealing of exposed collagen fibers in prepared teeth, the use of nano fillers or nano gels has been tried [21]. Reactive nanogels [22], zirconia (20–50 nm) [23], HA (20–70 nm) [24], colloidal silica (5–40 nm) or barium aluminosilicate nanofillers (400 nm) [25], and bioactive calcium/sodium phosphosilicate [21] are some examples of nano materials. Self-healing adhesives that can patch up microscopic or nanoscale cracks without compromising the strength of resin-dentin connections have also been developed [26]. They contain nano capsules that are packed with healing agents, and the presence of a break in the resin matrix typically causes the nano capsules to burst and release their contents. The durability of the resin-dentin interface has also been improved by using nano-controlled molecular interaction between the resin monomer and HA that is still present in the hybrid layer [27]. In comparison to fine size fillers, nano fillers offer superior adherence, biocompatibility, and durability. Many scientific organizations are using hydroxyapatite (HA), the primary inorganic mineral component of teeth, to create nano composites. To serve as an inorganic component of nano composites, Chung et al. created a physiological component mixture using HA and chitosan nanoparticles [28]. By creating HP-gelatin/curcumin nanocomposites, antimicrobial properties against Escherichia coli, Staphylococcus aureus, and Streptococcus mutans were introduced into filler materials [29]. Various natural polymers have been employed in investigations to alter the organic nanocomposites' organic component characteristics [30]. The strongest antibacterial HA/CuO/TiO_2 nanocomposites were created by Imani et al. The strong Quality by Design principle assisted in the manifestation of development [31]. A difficult challenge to incorporate Ag NPs, graphene oxide (GO), multi-walled carbon nanotubes (MWCNTs), and graphene oxide nanoribbons (GONRs) in HA nanocomposites was recently undertaken by Balu et al. The team investigated how the amount of carbon affected the final hardness of the nanocomposites. Additionally, a bio strain was used to assess the Ag NPs activity (E. coli and S. aureus bacteria). Lidocaine was made available as a model drug release by the created nanocomposite [32].

As a supplementary material in the creation of nanocomposites, other synthetic polymers have been investigated. Poly Methyl Methacrylate Nanocomposites have improved mechanical properties as compared to HA nanocomposites [33]. Mallakpour et al. developed multi-component nanocomposites (Polyvinylpyrrolidone/L-leucine Amino Acid, Functionalized Mg-Substituted Fluorapatite Nanocomposites) using ultrasonic waves as an energy source [34]. Microwaves [35–37], photons [38] and their combinations [39] are other energy sources that have been used by various research groups to create nano composites.

Open tubules are brushed with highly concentrated GNPs to prevent pain and suffering in dentinal hypersensitivity, and laser irradiation is used to encourage the aggregation of nanoparticles to cover the exposed tubules [40]. Additionally, dental nanorobots provide a rapid and effective treatment for dentin hypersensitivity by accurately and selectively occluding the tubules with biological materials in a matter of minutes [4].

5 Applications in Endodontics Treatment

The innermost, most important, and vascular component of a tooth is the dental pulp, which is made up of nerve fibers and blood vessels. The area of dentistry known as endodontics deals with periodontal tissues and dental pulp. When an infection penetrates the dentin and enamel to reach the pulp, pulp treatment is necessary. Cleaning and preparing root canals that contain pulp tissues for an appropriate filling and sealing material is the focus of endodontics. The following qualities should be present in an ideal root-end filling material: a hermetic seal, non-resorb ability, non-toxicity, non-carcinogenicity, biocompatibility, and dimensional stability [41–43]. None of the materials in existence satisfies every requirement. To sanitize root canals, root canal sealers contain a number of nanoparticles, including zinc oxide and chitosan alone or in combination. The flow characteristics of the sealers were unaffected, but they improved the antibacterial action, as evidenced by a notable decrease in Enterococcus faecalis adhering to treated dentin [44]. It was possible to retain the inhibitory impact of a chitosan-modified root canal sealer on biofilm growth at the sealer-dentin interface by first treating the surface of root canal dentin with phosphorylated chitosan [45]. Metal oxides, including magnesium oxide nanoparticles, show promised antibacterial activity in both in vitro and ex vivo tests and may be employed as a possible root canal irrigant. Magnesium oxide nanoparticles (5 mg/L) show a statistically significant long-term benefit in the removal of E as compared to the usual NaOCl solution (5.25%). Faecalis adhered to the dentin of the root canal [46].

Nano materials that aim to regenerate pulp tissue could improve endodontic treatment by preserving the health of the pulp and, by extension, the structural integrity of the tooth. Dentin Odontoblast (located at the edge of the pulp) stem cells have also been investigated for this purpose; however, the clinical setup showed a futile response [47, 48]. Hanafy et al. investigated two widely used dental biomaterials, namely mineral trioxide aggregate (MTA) and nano-HA, as odontogenic differentiation promotors. The results showed significantly higher and upregulated expression of the odontotomy differentiation-specific genes, namely OPN, RUNX2, OCN, and Collagen1, in the treatment group compared to the control group [49]. Another strategy to keep the pulp healthy and keep the infection outside the vascular area is pulp capping. Li et al. suggested a combination of micro-nano bioactive glasses with biocompatible, osteogenesis-sensitizing characteristics. Dental pulp capping using Ca–Zn–Si-based micro nanospheres (Zn doped). The results were positive, showing increased antibacterial effects and increased macrophage stimulation to decrease proinflammatory indicators, followed by dentin remineralization via sensitization of dental pulp cells [50]. Drug-encapsulated liposomes were suggested by Sinjari et al. as a very sophisticated nanotechnological method for restoring the homeostasis of dental pulp stem cells. In terms of 2-hydroxyethyl methacrylate, the treatment was able to help restore cell proliferation and reduce inflammation markers [51]. Kim et al. have suggested an RGD peptide conjugated dendrimer-based medication delivery system for dental pulp differentiation following severe dental injury. Higher mineralization and odontogenic potential were very positive findings [52]. With a very small number of tests, Elgendy and Fayyad investigated natural scaffolds, such as propolis and chitosan, for tooth restoration and discussed their potential for endodontic treatment because of their high biocompatibility and capacity for tissue restoration [53]. In a similar vein, Tondnevis et al. suggested creating a dental tissue scaffold utilizing polymers and the freeze-drying method that contains nano-HA or Nano-Fluro HA/Chitosan scaffold. Results showed that chitosan was helpful in significantly increasing cell proliferation [54]. These experiments demonstrated the chitosan NPs' potential for use in dental endodontics. The role of eggshell-derived porous nano-HA and CMC (Carboxy Methylcellulose) composite was recently reported in a laboratory study by Baskar et al., which demonstrated their impact on dental bioactivity and cell proliferation using the significantly increased levels of VEGF and dentine sialo phosphoprotein [55]. The development and testing of amoxicillin-loaded nanodiamond Gutta-percha composite (NDGP-AMC) for use in root canal procedures produced encouraging results [56]. Gelatin [57–59], collagen [60], silk [59], and other natural fibers and polymers have also been investigated in nano dentistry.

6 Applications in Orthodontic Treatment

To realign teeth, force must be applied in the desired direction and interfacial stability must exist between the tooth surface, bracket, arch wire, and ligatures, among others [61]. Better holding and stability are prevented by the frictional forces between the arch wire and the brackets, which can also lengthen the course of treatment and have an impact on the final result. These components are covered with Fullerene, such as Molybdenum and tungsten disulfide NPs, to lessen this friction [61]. Also, nanotechnology can help in maintaining better oral hygiene, better anchorage, and lesser enamel demineralization during orthodontic treatment by several coatings like elastomeric ligatured supported NPs (Benzocaine and Ag) [62], nanocomposites (Ag NPs with ZnO, chlorhexidine) of adhesive types/bands [63], gold NPs in orthodontic adhesives [64], silver NPs [65], TiO_2 NPs [66], and copper oxide NPs [67].

7 Applications in Prosthodontic Treatment

Patients are increasingly more likely to seek out rehabilitation therapy as a result of greater awareness of and interest in quality-of-life enhancement. Nanotechnology is now a component of materials for crown, bridge, and implants used in restorative dentistry as a result of progress in research aimed at improving tooth replacement. The qualities of currently employed materials, including ceramics, impression materials, denture bases, and different forms of prosthodontic cement, have also been greatly improved by nanotechnology. Polymethylmethacrylate (PMMA) polymers are mostly used in removable prosthodontic appliances such as complete dentures, partial dentures, and detachable maxillofacial prostheses. Chlorinated polyethylene, poly(methyl methacrylate), poly(urethane), poly(vinyl chloride), and poly(dimethylsiloxane) (PDMS—silicone elastomers) have all been employed in the production of maxillofacial prosthesis [68]. Although PMMA has strong biocompatibility, aesthetics, processability, and reparability, it has the drawbacks of being weak, having a low fracture resistance, behaving radiopacitively, and having microbial adherence

[69–71]. Well-dispersed nano-ZrO_2 particles can increase the strength, modulus, and ductility while TiO_2 nanoparticles strengthened the mechanical behavior of PMMA. Particles of Ag TiO_2 and Fe_2O_3 considerably lessen C's adhesion. albicans made of PMMA that have no impact on growth or metabolism [72–74]. It can aid in treating pathological conditions such as denture stomatitis brought on by Candida albicans adhering to the denture base materials [75]. Due to their sophisticated mechanical and physical qualities, silicone elastomers have been employed in the production of dental prosthesis for a long time [76]. They are also non-toxic, chemically resistant, and biocompatible. PDMS [77, 78] and silicone rubber are the most preferred types [79–81]. In recent studies, various filler nanoparticles (NPs) have been added to silicone rubbers to enhance their physical and mechanical properties through [82]. The silicone matrix is most frequently reinforced using silica NPs as fillers [82, 83]. Silicone elastomers' mechanical and physical properties would vary depending on the concentration of silica NPs present [82, 84]. Additionally, silicone elastomers are supported by polyhedral oligomeric silsesquioxanes (POS), a nano (1.5 nm) silica cage, and metal nanoparticles (NPs) to enhance their tensile strength and other physical characteristics. Fixed prosthesis can use nano materials, nanocomposites, and nano coatings. Cytotoxicity brought on by the leaching of organic monomers can be resolved by nanocomposites built on nanofiller technology. To increase flexural strength and hardness, 3-methacryloxypropyl-tri-methoxy-silane was applied to silica particles to create zirconia-silica nanoparticles. Nanotechnology offers new opportunities and promises for enhancing the adherence and endurance of implants. In addition to calcium phosphate, silica-based NPs, polyvinyl alcohol, and carbon nanotubes were employed to create nanocomposites and occasionally scaffolds for enhancing mechanical strength and tissue regeneration [85]. The most recent developments in research on the uses of nanometals, nanoceramics, nanoresins, and other nano materials in prosthodontics have been reviewed. This research clearly demonstrates that many properties of materials used in prosthodontics, such as modulus elasticity, surface hardness, polymerization shrinkage, and filler loading, can be significantly improved after their scales were reduced from micron-size into nano size by nanotechnology.

8 Application in Dental Implants

Nanostructure-modified titanium implants encourage osteogenic differentiation and could have a better bio-integration into the alveolar bone [86]. The flat surface of titanium implants can be anodized to create nanotubular structures with a diameter of less than 100 nm [87]. The physicochemical characteristics of surfaces [88], as well as the spacing and diameter of nanotubes, can be controlled by altering variables including voltage, current density, and the chemistry of the electrolyte. Long nano tube arrays (10 m) and pillar-like nanostructures with adjustable sizes are also deposited by anodization on titanium surfaces [89]. On Titanium, Ti6Al4V, Cr–Co–Mo alloys, and Tantalum, nano pit networks (pit diameter 20–100 nm) can be successfully created by combining strong acids or bases with oxidants. According to a study, treatment with HCl produces superior outcomes than those with H_2SO_4 and $Na_2S_2O_8$ [90]. Acid etching can be used in conjunction with other procedures, such as grit blasting, to remove contaminants on implant surfaces by blasting residues. The titanium dental implants' osseointegration could be hampered by the grit blasting residue. But compared to an acid-etched surface, the nanostructured Ti surface created by physical vapor deposition had a surface area increase of up to 40% and a stronger osseointegration. Additionally, to improve bone regeneration, HA nanocrystals [91] and calcium-phosphorus NPs [92] can be used to treat or modify the implant surface. A wide range of distinctive nanostructures, including octahedral bipyramids, nano flowers, nano needles, nano rods, and meso-porous nano scaffolds, have been produced on titanium using a combination of hydrothermal treatments (tuning concentration, temperature, reaction medium composition, and time duration) and sodium hydroxide [93]. Early bone healing and improved mechanical interlocking with bone result from the deposition of discrete 20–40 nm nanoparticles on a dual acid-etched implant surface. Niobium oxide and diamond-like carbon nano topographies have been produced on titanium and other substrates with the aid of a mixture of chemical vapor deposition and the sol–gel method, improving the bioactivity of implantable metals. Other current techniques for creating a nanostructured dental implant surface include laser technology and coatings made of ultraviolet (UV) photo functionalized (picometer to nanometer) TiO_2 [94].

9 Applications Preventive Therapy

Anticaries DNA vaccine's immunogenicity has been improved by the use of customized delivery vehicles, such as anionic liposomes in chitosan/DNA nanoparticle complexes. In order to permit the release of the vaccine in a pH-dependent way, the surface charge of the delivery vehicle may also be pH-dependent. All in vitro research up to this point has suggested that nanotechnology may be able to stop the progression of early caries lesions in their surface but not deeper layers. A local application of a nanostructured doxycycline gel has been employed in an experimental periodontal disease model to stop bone loss. With their continuous and quick movement (1–10 m/s) across the supra and subgingival surfaces, nanorobots (dentifrobots) mouthwash or toothpaste left on the occlusal surfaces of teeth continually remove the organic residues and prevent the calculus accumulation. When eaten, these nanorobots can be safely deactivated [95]. A number of oral health care products, including liquids and pastes containing nano-appetite for managing biofilm at the tooth surface and goods including nano materials for remineralizing early submicrometric sized enamel defects, have been developed using biomimetic techniques. On the tooth surface, bacteria form biofilms that lead to dental cavities. Nanocomposite surface coatings can minimize bacterial adhesion, prevent pathogenic effects, and make the tooth surface easier to clean. The apatite nanoparticle-containing toothpaste can be employed as biofilm management nano materials and as a method for remineralizing enamel lesions that are smaller than sub-micrometers [96–98]. However, these oral nanoparticle preventive medications are still in the research phase, and further in-depth research is required before they can be used in clinical settings. Several nanoparticles, like zinc oxide, silver, and polyethyleneimine, can be incorporated into dental composites or dental adhesives to give antibacterial nano treatment. This inhibits the growth of germs through a variety of ways. The bacterial cell membrane is disrupted, sugar metabolism and active transport are both inhibited, reactive oxygen species are produced, magnesium ions necessary for the enzymatic activity of oral biofilms are displaced, electron transport across the bacterial membrane is disturbed, and DNA replication is prevented [99, 100].

10 Applications in Regenerative Therapy

Different types of nano-calcium phosphates, including dicalcium phosphate anhydrous, tetra calcium phosphate, monocalcium phosphate monohydrate, and carbonate hydroxyapatite, have been employed as Ca- and PO-releasing fillers for remineralization in recurrent caries [101, 102]. Similar to other medical fields, tissue engineering in dentistry has been used to integrate scaffold matrices with the regeneration abilities of stem cells, which are mostly derived from dental tissues such as dental pulp, periodontal ligament (PDL), and alveolar bone. These scaffolding materials have been significantly improved thanks to nanotechnology in tissue engineering, creating special 3D matrix conditions for cells and tissues. A native tissue architecture can be developed using a bottom up method, giving an engineered construct the mechanical properties of enamel and dentin [103]. The dental tissues' nanoarchitecture is used to create electro spun nanofibers, self-assembling peptides, and phase-separation matrices. The development of nanofibrous scaffolds as matrices for the regeneration of dental tissues, such as the dentin-pulp complex, enamel, PDL, cementum, alveolar bone, and temporomandibular joint, has been widespread [104, 105].

11 Conclusion

Nano dentistry attracts patients to dentistry because it is cost-effective, saves time, and prevents psychological trauma. More patient-centered research will aid in the advancement of nanotheranostics that are both effective and cost-effective. Despite the numerous irrefutable gaps that limit its clinical exploration, revolutionary nanotechnology has enhanced conventional dentistry. Research in the field of nano dentistry still lags behind other areas of biological study. Prior to the application of nanotechnology on a large scale, fundamental molecular engineering methods, mass production techniques, and the simultaneous coordination of many nanorobots must be overcome. Nanotechnology advancements are shaping the future of healthcare administration. They have the potential to produce significant benefits, such as improved health, more efficient use of natural resources, and less environmental pollution. Nanotechnology will profoundly alter dentistry, healthcare, and human life. However, social issues of public acceptance, ethics, regulation, and human safety must be addressed prior to the incorporation of molecular nanotechnology into the modern medical and dental arsenal.

References

1. Drexler KE (2004) Nanotechnology: from Feynman to funding. Bull Sci Technol Soc 24(1):21–27. https://doi.org/10.1177/0270467604263113
2. Mansoori GA (2005) Advances in atomic and molecular nanotechnology. In: Principles of nanotechnology, pp. 1–30. https://doi.org/10.1142/9789812569318_0001
3. Rieth M (2003) Nano-engineering—studies and conclusions. In: Nano-engineering in science and technology, pp. 91–132. https://doi.org/10.1142/9789812560032_0005
4. Freitas RA (2000) Nanodentistry. J Am Dent Assoc 131(11):1559–1565. https://doi.org/10.14219/jada.archive.2000.0084
5. Robert A Nanomedicine. Basic capabilities, vol I, 1st edn. https://www.routledge.com/Nanomedicine-Volume-I-Basic-Capabilities/Freitas/p/book/9781570596803?_ga=2.41737122.1878036391.1680456715-375155477.1680456715&_gl=1*1p2e9cf*_ga*MTM3NTE1NTQ3Ny4xNjgwNDU2NzE1*_ga_0HYE8YG0M6*MTY4MDQ1NjcxNi4xLjEuMTY4MDQ1NjgzOS4wLjAuMA. Accessed 2 Apr 2023
6. Abou Neel EA, Bozec L, Perez RA, Kim H-W, Knowles JC (2015) Nanotechnology in dentistry: prevention, diagnosis, and therapy. Int J Nanomed 10:6371–6394. https://doi.org/10.2147/IJN.S86033
7. Bapat RA et al (2019) The use of nanoparticles as biomaterials in dentistry. Drug Discov Today 24(1):85–98. https://doi.org/10.1016/j.drudis.2018.08.012
8. Yudaev P, Chuev V, Klyukin B, Kuskov B, Mezhuev Y, Chistyakov E (2022) Polymeric dental nanomaterials: antimicrobial action. Polymers 14(5). https://doi.org/10.3390/polym14050864
9. Yang J, Zhang Z, Men X, Xu X (2009) Fabrication of stable, transparent and superhydrophobic nanocomposite films with polystyrene functionalized carbon nanotubes. Appl Surf Sci 255(22). https://doi.org/10.1016/j.apsusc.2009.07.010
10. Chen C et al (2014) Antibacterial activity and ion release of bonding agent containing amorphous calcium phosphate nanoparticles. Dent Mater 30(8):891–901. https://doi.org/10.1016/J.DENTAL.2014.05.025
11. Subramani K, Jung RE, Molenberg A, Hammerle CHF (2009) Biofilm on dental implants: a review of the literature. Int J Oral Maxillofac Implants 24(4):616–626
12. Abe Y, Skali-Lami S, Block JC, Francius G (2012) Cohesiveness and hydrodynamic properties of young drinking water biofilms. Water Res 46(4):1155–1166. https://doi.org/10.1016/J.WATRES.2011.12.013
13. Pinzón-Arango PA, Nagarajan R, Camesano TA (2010) Effects of L-alanine and inosine germinants on the elasticity of bacillus anthracis spores. Langmuir 26(9):6535–6541. https://doi.org/10.1021/LA904071Y/ASSET/IMAGES/MEDIUM/LA-2009-04071Y_0006.GIF
14. Zhang T, Chao Y, Shih K, Li XY, Fang HHP (2011) Quantification of the lateral detachment force for bacterial cells using atomic force microscope and centrifugation. Ultramicroscopy 111(2):131–139. https://doi.org/10.1016/J.ULTRAMIC.2010.10.005
15. Yang X et al (2010) Atomic force microscopy investigation of the characteristic effects of silver ions on Escherichia coli and Staphylococcus epidermidis. Talanta 81(4–5):1508–1512. https://doi.org/10.1016/J.TALANTA.2010.02.061

16. McKendry RA (2012) Nanomechanics of superbugs and superdrugs: new frontiers in nanomedicine. Biochem Soc Trans 40(4):603–608. https://doi.org/10.1042/BST20120082
17. Sullan RMA et al (2014) Single-cell force spectroscopy of pili-mediated adhesion. Nanoscale 6(2). https://doi.org/10.1039/c3nr05462d
18. Longo G et al (2012) Force volume and stiffness tomography investigation on the dynamics of stiff material under bacterial membranes. J Mol Recognit 25(5):278–284. https://doi.org/10.1002/JMR.2171
19. Malacarne-Zanon J et al (2010) Permeability of dental adhesives—a SEM assessment. Eur J Dent 4(4):429–439
20. Hashimoto M et al (2004) In vitro effect of nanoleakage expression on resin-dentin bond strengths analyzed by microtensile bond test, SEM/EDX and TEM. Biomaterials 25(25). https://doi.org/10.1016/j.biomaterials.2004.01.009
21. Profeta AC, Mannocci F, Foxton RM, Thompson I, Watson TF, Sauro S (2012) Bioactive effects of a calcium/sodium phosphosilicate on the resin-dentine interface: a microtensile bond strength, scanning electron microscopy, and confocal microscopy study. Eur J Oral Sci 120(4). https://doi.org/10.1111/j.1600-0722.2012.00974.x
22. Morães RR et al (2012) Improved dental adhesive formulations based on reactive nanogel additives. J Dent Res 91(2). https://doi.org/10.1177/0022034511426573
23. Lohbauer U et al (2010) Zirconia nanoparticles prepared by laser vaporization as fillers for dental adhesives. Acta Biomater 6(12). https://doi.org/10.1016/j.actbio.2010.07.002
24. Wagner A, Belli R, Stötzel C, Hilpert A, Müller FA, Lohbauer U (2013) Biomimetically-and hydrothermally-grown HAp nanoparticles as reinforcing fillers for dental adhesives. J Adhes Dent 15(5). https://doi.org/10.3290/j.jad.a29534
25. Di Hipólito V, Reis AF, Mitra SB, de Goes MF (2012) Interaction morphology and bond strength of nanofilled simplified-step adhesives to acid etched dentin. Eur J Dent 6(4):349–360
26. Ouyang X et al (2011) Synthesis and characterization of triethylene glycol dimethacrylate nanocapsules used in a self-healing bonding resin. J Dent 39(12). https://doi.org/10.1016/j.jdent.2011.09.001
27. Yoshihara K et al (2010) Nano-controlled molecular interaction at adhesive interfaces for hard tissue reconstruction. Acta Biomater 6(9). https://doi.org/10.1016/j.actbio.2010.03.024
28. Chung JH et al (2016) Synthesis, characterization, biocompatibility of hydroxyapatite-natural polymers nanocomposites for dentistry applications. Artif Cells Nanomed Biotechnol 44(1). https://doi.org/10.3109/21691401.2014.944644
29. Sharifi S, Khosroshahi AZ, Dizaj SM, Rezaei Y (2022) Preparation, physicochemical assessment and the antimicrobial action of hydroxyapatite–gelatin/curcumin nanofibrous composites as a dental biomaterial. Biomimetics 7(1). https://doi.org/10.3390/biomimetics7010004
30. Abdelshafi MA, Fathy SM, Elkhooly TA, Reicha FM, Osman MF (2021) Bond strength of demineralized dentin after synthesized collagen/hydroxyapatite nanocomposite application. J Mech Behav Biomed Mater 121. https://doi.org/10.1016/j.jmbbm.2021.104590
31. Imani MM, Kiani M, Rezaei F, Souri R, Safaei M (2021) Optimized synthesis of novel hydroxyapatite/CuO/TiO_2 nanocomposite with high antibacterial activity against oral pathogen Streptococcus mutans. Ceram Int 47(23). https://doi.org/10.1016/j.ceramint.2021.08.246
32. Balu SK, Sampath V, Andra S, Alagar S, Manisha Vidyavathy S (2021) Fabrication of carbon and silver nanomaterials incorporated hydroxyapatite nanocomposites: enhanced biological and mechanical performances for biomedical applications. Mater Sci Eng C 128. https://doi.org/10.1016/j.msec.2021.112296
33. Rashahmadi S, Hasanzadeh R, Mosalman S (2017) Improving the mechanical properties of poly methyl methacrylate nanocomposites for dentistry applications reinforced with different nanoparticles. Polym - Plast Technol Eng 56(16). https://doi.org/10.1080/03602559.2017.1289402
34. Mallakpour S, Khani M, Mallakpour F, Fathi M (2018) Preparation and characterization of polyvinylpyrrolidone/L-leucine amino acid–modified montmorillonite/chiral diacid–functionalized Mg-substituted fluorapatite nanocomposites by ultrasonic-assisted rapid process. Polym - Plast Technol Eng 57(1). https://doi.org/10.1080/03602559.2017.1298804

35. Deng F, Fu LH, Ma MG (2015) Microwave-assisted rapid synthesis and characterization of CaF_2 particles-filled cellulose nanocomposites in ionic liquid. Carbohydr Polym 121. https://doi.org/10.1016/j.carbpol.2014.12.033
36. Sözügeçer S, Bayramgil NP (2021) Preparation and characterization of polyacrylic acid-hydroxyapatite nanocomposite by microwave-assisted synthesis method. Heliyon 7(6). https://doi.org/10.1016/j.heliyon.2021.e07226
37. Karthik K, Dhanuskodi S, Gobinath C, Prabukumar S, Sivaramakrishnan S (2018) Multifunctional properties of microwave assisted CdO–NiO–ZnO mixed metal oxide nanocomposite: enhanced photocatalytic and antibacterial activities. J Mater Sci: Mater Electron 29(7). https://doi.org/10.1007/s10854-017-8513-y
38. Raho R, Paladini F, Lombardi FA, Boccarella S, Zunino B, Pollini M (2015) In-situ photo-assisted deposition of silver particles on hydrogel fibers for antibacterial applications. Mater Sci Eng C 55. https://doi.org/10.1016/j.msec.2015.05.050
39. Aseena S, Abraham N, Suresh Babu V (2019) Synthesis of ZnO/CNT nanocomposite by microwave and ultrasound assisted two step process. In: Proceedings—international conference on vision towards emerging trends in communication and networking, ViTECoN 2019. https://doi.org/10.1109/ViTECoN.2019.8899366
40. Liu MH, Chan CH, Ling JH, Chris Wang CR (2007) Filling in dentinal tubules. Nanotechnology 189(47):475104. https://doi.org/10.1088/0957-4484/18/47/475104
41. Fallis AG (2013) Ingle's endodontics 6, vol 53, no 9
42. Arens D, Torabinejad M, Chivian N, Rubinstein R (1998) Practical lessons in endodontic surgery
43. Gartner AH, Dorn SO (1992) Advances in endodontic surgery. Dent Clin N Am 36(2). https://doi.org/10.1016/s0011-8532(22)02501-0
44. Kishen A, Shi Z, Shrestha A, Neoh KG (2008) An investigation on the antibacterial and antibiofilm efficacy of cationic nanoparticulates for root canal disinfection. J Endod 34(12). https://doi.org/10.1016/j.joen.2008.08.035
45. Lu Z, Rong K, Li J, Yang H, Chen R (2013) Size-dependent antibacterial activities of silver nanoparticles against oral anaerobic pathogenic bacteria. J Mater Sci Mater Med 24(6):1465–1471. https://doi.org/10.1007/S10856-013-4894-5
46. Monzavi A, Eshraghi S, Hashemian R, Momen-Heravi F (2015) In vitro and ex vivo antimicrobial efficacy of nano-MgO in the elimination of endodontic pathogens. Clin Oral Investig 19(2):349–356. https://doi.org/10.1007/S00784-014-1253-Y/FIGURES/2
47. Suzuki T et al (2011) Induced migration of dental pulp stem cells for in vivo pulp regeneration. J Dent Res 90(8):1013–1018. https://doi.org/10.1177/0022034511408426/SUPPL_FILE/DS_10.1177_0022034511408426.PDF
48. Rodríguez-Lozano FJ, Guerrero-Gironés J, Pecci-Lloret MR, Pecci-Lloret MP (2022) Stem cells for endodontic regeneration. In: Biomaterials in endodontics, pp. 273–283. https://doi.org/10.1016/B978-0-12-821746-7.00012-7
49. Hanafy AK, Shinaishin SF, Eldeen GN, Aly RM (2018) Nano hydroxyapatite & mineral trioxide aggregate efficiently promote odontogenic differentiation of dental pulp stem cells. Open Access Maced J Med Sci 6(9):1727. https://doi.org/10.3889/OAMJMS.2018.368
50. Li Z, Xie K, Yang S, Yu S, Xiao Y, Zhou Y (2021) Multifunctional Ca-Zn-Si-based micro-nano spheres with anti-infective, anti-inflammatory, and dentin regenerative properties for pulp capping application. J Mater Chem B 9(39). https://doi.org/10.1039/d1tb01517f
51. Sinjari B et al (2019) Curcumin/liposome nanotechnology as delivery platform for anti-inflammatory activities via NFkB/ERK/pERK pathway in human dental pulp treated with 2-HydroxyEthyl MethAcrylate (HEMA). Front Physiol 10:633. https://doi.org/10.3389/FPHYS.2019.00633/BIBTEX
52. Kim JK et al (2010) Differentiating dental pulp cells via RGD-dendrimer conjugates. 89(12):1433–1438. https://doi.org/10.1177/0022034510384870
53. Elgendy AA, Fayyad DM (2017) Cell viability and apoptotic changes of dental pulp stem cells treated with propolis, chitosan, and their nano counterparts. Tanta Dent J 14(4):198. https://doi.org/10.4103/TDJ.TDJ_27_17

54. Tondnevis F, Ketabi M, Fekrazad R, Sadeghi A, Abolhasani MM (2019) Using chitosan besides nano hydroxyapatite and fluorohydroxyapatite boost dental pulp stem cell proliferation. J Biomim, Biomater Biomed Eng 42:39–50. https://doi.org/10.4028/WWW.SCIENTIFIC.NET/JBBBE.42.39
55. Baskar K et al (2022) Eggshell derived nano-hydroxyapatite incorporated carboxymethyl chitosan scaffold for dentine regeneration: a laboratory investigation. Int Endod J 55(1):89–102. https://doi.org/10.1111/IEJ.13644
56. Lee DK et al (2015) Nanodiamond-gutta percha composite biomaterials for root canal therapy. ACS Nano 9(11):11490–11501. https://doi.org/10.1021/ACSNANO.5B05718
57. Vagropoulou G et al (2021) Hybrid chitosan/gelatin/nanohydroxyapatite scaffolds promote odontogenic differentiation of dental pulp stem cells and in vitro biomineralization. Dent Mater 37(1):e23–e36. https://doi.org/10.1016/J.DENTAL.2020.09.021
58. Alipour M et al (2021) The antimicrobial, antioxidative, and anti-inflammatory effects of polycaprolactone/gelatin scaffolds containing chrysin for regenerative endodontic purposes. Stem Cells Int 2021. https://doi.org/10.1155/2021/3828777
59. Alipour M et al (2021) The osteogenic differentiation of human dental pulp stem cells in alginate-gelatin/nano-hydroxyapatite microcapsules. BMC Biotechnol 21(1). https://doi.org/10.1186/S12896-020-00666-3
60. Ilyas K et al (2018) Microwave-assisted synthesis and evaluation of type 1 collagen–apatite composites for dental tissue regeneration. 33(1):103–115. https://doi.org/10.1177/0885328218773220
61. de Stefani A, Bruno G, Preo G, Gracco A (2020) Application of nanotechnology in orthodontic materials: a state-of-the-art review. Dent J 8(4):126. https://doi.org/10.3390/DJ8040126
62. Yin IX, Zhang J, Zhao IS, Mei ML, Li Q, Chu CH (2020) The antibacterial mechanism of silver nanoparticles and its application in dentistry. Int J Nanomed 15. https://doi.org/10.2147/IJN.S246764
63. Bapat RA et al (2018) An overview of application of silver nanoparticles for biomaterials in dentistry. Mater Sci Eng C 91. https://doi.org/10.1016/j.msec.2018.05.069
64. Akarajarasrod P et al (2021) Antibacterial effect of experimental orthodontic adhesives containing gold nanoparticles against Streptococcus mutans and Streptococcus sobrinus. Key Eng Mater 904:301–308. https://doi.org/10.4028/WWW.SCIENTIFIC.NET/KEM.904.301
65. Alam MK, Alsuwailem R, Alfawzan AA (2022) Antibacterial activity and bond strength of silver nanoparticles modified orthodontic bracket adhesive: a systematic review and meta-analysis of in-vitro and in-vivo studies. Int J Adhes Adhes 113:103040. https://doi.org/10.1016/J.IJADHADH.2021.103040
66. Poosti M, Ramazanzadeh B, Zebarjad M, Javadzadeh P, Naderinasab M, Shakeri MT (2013) Shear bond strength and antibacterial effects of orthodontic composite containing TiO_2 nanoparticles. Eur J Orthod 35(5). https://doi.org/10.1093/ejo/cjs073
67. Eshed M, Lellouche J, Matalon S, Gedanken A, Banin E (2012) Sonochemical coatings of ZnO and CuO nanoparticles inhibit streptococcus mutans biofilm formation on teeth model. Langmuir 28(33). https://doi.org/10.1021/la301432a
68. Eleni PN, Katsavou I, Krokida MK, Polyzois GL, Gettleman L (2009) Mechanical behavior of facial prosthetic elastomers after outdoor weathering. Dent Mater 25(12). https://doi.org/10.1016/j.dental.2009.06.018
69. Mehra M, Vahidi F, Berg RW (2014) A complete denture impression technique survey of postdoctoral prosthodontic programs in the United States. J Prosthodont 23(4). https://doi.org/10.1111/jopr.12099
70. Cuy JL, Mann AB, Livi KJ, Teaford MF, Weihs TP (2002) Nanoindentation mapping of the mechanical properties of human molar tooth enamel. Arch Oral Biol 47(4). https://doi.org/10.1016/S0003-9969(02)00006-7
71. Webster TJ, Ejiofor JU (2004) Increased osteoblast adhesion on nanophase metals: Ti, Ti6Al4V, and CoCrMo. Biomaterials 25(19). https://doi.org/10.1016/j.biomaterials.2003.12.002

72. dos Santos JG, Fonseca RG, Adabo GL, dos Santos Cruz CA (2006) Shear bond strength of metal-ceramic repair systems. J Prosthet Dent 96(3). https://doi.org/10.1016/j.prosdent.2006.07.002
73. Van Bael S, Kerckhofs G, Moesen M, Pyka G, Schrooten J, Kruth JP (2011) Micro-CT-based improvement of geometrical and mechanical controllability of selective laser melted Ti6Al4V porous structures. Mater Sci Eng, A 528(24):7423–7431. https://doi.org/10.1016/J.MSEA.2011.06.045
74. Liu Z, Zhang X, Xuan F, Wang Z, Tu S (2013) Effect of laser power on the microstructure and mechanical properties of TiN/Ti3Al composite coatings on Ti6Al4V. Chin J Mech Eng (Engl Ed) 26(4). https://doi.org/10.3901/CJME.2013.04.714
75. Gendreau L, Loewy ZG (2011) Epidemiology and etiology of denture stomatitis. J Prosthodont 20(4). https://doi.org/10.1111/j.1532-849X.2011.00698.x
76. Jindal SK, Sherriff M, Waters MG, Smay JE, Coward TJ (2018) Development of a 3D printable maxillofacial silicone: part II. Optimization of moderator and thixotropic agent. J Prosthet Dent 119(2). https://doi.org/10.1016/j.prosdent.2017.04.028
77. Bellamy K, Limbert G, Waters MG, Middleton J (2003) An elastomeric material for facial prostheses: synthesis, experimental and numerical testing aspects. Biomaterials 24(27). https://doi.org/10.1016/S0142-9612(03)00412-5
78. Jindal SK, Sherriff M, Waters MG, Coward TJ (2016) Development of a 3D printable maxillofacial silicone: part I. Optimization of polydimethylsiloxane chains and cross-linker concentration. J Prosthet Dent 116(4). https://doi.org/10.1016/j.prosdent.2016.02.020
79. Makode S, Singh G, Chanda A (2021) Development of novel anisotropic skin simulants. Phys Scr 96:125019. https://doi.org/10.1088/1402-4896/AC2EFD
80. Singh G, Chanda A (2023) Development and mechanical characterization of artificial surrogates for brain tissues. Biomed Eng Adv 5:100084. https://doi.org/10.1016/J.BEA.2023.100084
81. Gupta V, Singh G, Chanda A (2023) Development of novel hierarchical designs for skin graft simulants with high expansion potential. Biomed Phys Eng Express 9:035024. https://doi.org/10.1088/2057-1976/ACC661
82. Cevik P, Eraslan O (2017) Effects of the addition of titanium dioxide and silaned silica nanoparticles on the mechanical properties of maxillofacial silicones. J Prosthodont 26(7). https://doi.org/10.1111/jopr.12438
83. Zayed SM, Alshimy AM, Fahmy AE (2014) Effect of surface treated silicon dioxide nanoparticles on some mechanical properties of maxillofacial silicone elastomer. Int J Biomater 2014. https://doi.org/10.1155/2014/750398
84. Goiato MC, Haddad MF, Pesqueira AA, Moreno A, dos Santos DM, Bannwart LC (2011) Effect of chemical disinfection and accelerated aging on color stability of maxillofacial silicone with opacifiers. J Prosthodont 20(7). https://doi.org/10.1111/j.1532-849X.2011.00755.x
85. Chaughule RS, Dashaputra R (2020) Advances in dental implantology using nanomaterials and allied technology applications. In: Advances in dental implantology using nanomaterials and allied technology applications, pp. 1–410. https://doi.org/10.1007/978-3-030-52207-0
86. Le Guéhennec L, Soueidan A, Layrolle P, Amouriq Y (2007) Surface treatments of titanium dental implants for rapid osseointegration. Dent Mater 23(7). https://doi.org/10.1016/j.dental.2006.06.025
87. Yao C, Slamovich EB, Webster TJ (2008) Enhanced osteoblast functions on anodized titanium with nanotube-like structures. J Biomed Mater Res A 85(1). https://doi.org/10.1002/jbm.a.31551
88. Park J, Bauer S, Schlegel KA, Neukam FW, Der Von Mark K, Schmuki P (2009) TiO_2 nanotube surfaces: 15 nm—an optimal length scale of surface topography for cell adhesion and differentiation. Small 5(6). https://doi.org/10.1002/smll.200801476
89. Sjöström T, Dalby MJ, Hart A, Tare R, Oreffo ROC, Su B (2009) Fabrication of pillar-like titania nanostructures on titanium and their interactions with human skeletal stem cells. Acta Biomater 5(5). https://doi.org/10.1016/j.actbio.2009.01.007

90. Takeuchi M, Abe Y, Yoshida Y, Nakayama Y, Okazaki M, Akagawa Y (2003) Acid pretreatment of titanium implants. Biomaterials 24(10). https://doi.org/10.1016/S0142-9612(02)00576-8
91. Yamada M et al (2012) Bone integration capability of nanopolymorphic crystalline hydroxyapatite coated on titanium implants. Int J Nanomed 7:859–873. https://doi.org/10.2147/IJN.S28082
92. Krupa D et al (2004) Effect of calcium and phosphorus ion implantation on the corrosion resistance and biocompatibility of titanium. Biomed Mater Eng 14(4):525–536
93. Rani VVD, Manzoor K, Menon D, Selvamurugan N, Nair SV (2009) The design of novel nanostructures on titanium by solution chemistry for an improved osteoblast response. Nanotechnology 20(19). https://doi.org/10.1088/0957-4484/20/19/195101
94. Sugita Y et al (2011) Effects of pico-to-nanometer-thin TiO_2 coating on the biological properties of microroughened titanium. Biomaterials 32(33). https://doi.org/10.1016/j.biomaterials.2011.07.077
95. Kumar S, Vijayalakshmi R (2006) Nanotechnology in dentistry. Indian J Dent Res 17(2):62. https://doi.org/10.4103/0970-9290.29890
96. Hannig M, Kriener L, Hoth-Hannig W, Becker-Willinger C, Schmidt H (2007) Influence of nanocomposite surface coating on biofilm formation in situ. J Nanosci Nanotechnol. https://doi.org/10.1166/jnn.2007.18117
97. Cross K, Huq N, Reynolds E (2007) Casein phosphopeptides in oral health—chemistry and clinical applications. Curr Pharm Des 13(8). https://doi.org/10.2174/138161207780363086
98. Reynolds EC, Cai F, Shen P, Walker GD (2016) Retention in plaque and remineralization of enamel lesions by various forms of calcium in a mouthrinse or sugar-free chewing gum. 82(3):206–211. https://doi.org/10.1177/154405910308200311
99. Gu H et al (2012) Effect of $ZnCl_2$ on plaque growth and biofilm vitality. Arch Oral Biol 57(4). https://doi.org/10.1016/j.archoralbio.2011.10.001
100. Song B, Leff LG (2006) Influence of magnesium ions on biofilm formation by Pseudomonas fluorescens. Microbiol Res 161(4). https://doi.org/10.1016/j.micres.2006.01.004
101. Xu HHK et al (2006) Nano DCPA-whisker composites with high strength and Ca and PO4 release. J Dent Res 85(8). https://doi.org/10.1177/154405910608500807
102. Roveri N et al (2008) Synthetic biomimetic carbonate-hydroxyapatite nanocrystals for enamel remineralization. Adv Mater Res. https://doi.org/10.4028/www.scientific.net/amr.47-50.821
103. He G, Dahl T, Veis A, George A (2003) Nucleation of apatite crystals in vitro by self-assembled dentin matrix protein 1. Nat Mater 2(8). https://doi.org/10.1038/nmat945
104. Ganesh N, Jayakumar R, Koyakutty M, Mony U, Nair SV (2012) Embedded silica nanoparticles in poly(caprolactone) nanofibrous scaffolds enhanced osteogenic potential for bone tissue engineering. Tissue Eng Part A 18(17–18). https://doi.org/10.1089/ten.tea.2012.0167
105. Woo KM, Chen VJ, Ma PX (2003) Nano-fibrous scaffolding architecture selectively enhances protein adsorption contributing to cell attachment. J Biomed Mater Res A 67(2). https://doi.org/10.1002/jbm.a.10098