Application of zinc oxide nanoparticles in dentistry

[1]Tandra Das. T, [2]Dr. Lakshmi. T

[1]Graduate Student, [2]Associate Professor
Saveetha dental college and hospital,
Saveetha institute of medical and technical sciences, Saveetha University,
Poonamalee, chennai-77

Abstract

Title: Application of zinc oxide nanoparticles in dentistry.

Aim: The aim of the review is to explore the use and advantage of zinc oxide nanoparticles in various aspects of dentistry.

Background: Nanotechnology is a research hot spot in modern materials science. NPs are known as controlled or manipulated particles at the atomic level (1–100 nm). They show size-related properties significantly different from bulk materials. Given their small size, NPs have larger structures in comparison with their counterparts. This distinct property allows their possible applications in many fields such as biosensors, nanomedicine, and bionanotechnology. The intrinsic properties of metal NPs such as zinc oxide (ZnO), TiO2, and silver are mostly characterized by their size, composition, crystallinity, and morphology. ZnO is currently being investigated as an antibacterial agent in both microscale and nanoscale formulations. ZnO exhibits significant antimicrobial activities when particle size is reduced to the nanometer range, then nano-sized ZnO can interact with bacterial surface and/or with the bacterial core where it enters inside the cell, and subsequently exhibits distinct bactericidal mechanisms.

Conclusion: This review emphasises on the use of zinc oxide nanoparticles in various aspects of dentistry. Most of the reports have shown more research and study has to be carried on zinc oxide Nano particles to incorporate it commonly in today's practice.

INTRODUCTION

Nanotechnology is a research hot spot in modern materials science. This advancement can be beneficial in extending miscellaneous novel applications that range from innovative fabric compounds, food processing, and agricultural production to sophisticated medicinal techniques [1]. It is considered as the synthesis, characterisation, and exploration of materials in the nanometer region (1–100 nm). The properties and functions of living and anthropogenic systems are defined at this level, [2]. In this automation, the most relatable materials are those whose structures exhibit new and considerably enhanced physicochemical and biological properties as well as distinct phenomena and functionalities as a result of the nanoscale size[3]. This macro sized generally confers lesser surface areas to nanoparticles (NPs) compared with nanoscale particles [4]. NPs are known as controlled or manipulated particles at the atomic level (1–100 nm). They show size-related properties significantly different from bulk materials[5] .Compared to their counter parts Nanoparticles have larger structures. This distinct property allows their possible applications in many fields such as biosensors, nanomedicine, and bionanotechnology [4].

The intrinsic properties of metal NPs such as zinc oxide (ZnO), TiO2, and silver are mostly characterised by their size, composition, crystallinity, and morphology. Reducing the size to nanoscale can modify their chemical, mechanical, electrical, structural, morphological, and optical properties. These modified features allow the NPs to interact in a unique manner with cell biomolecules and thus facilitate the physical transfer of NPs into the inner cellular structures [6]. Nanostructured materials have a larger percentage of atoms at their surface which lead to high surface reactivity. Thus, nanomaterials have witnessed recently significant importance in the basic and applied sciences as well as in bionanotechnology. Nano-sized ZnO exhibits varying morphologies and shows significant antibacterial activity over a wide spectrum of bacterial species explored by a large body of researchers [5,7-13]. ZnO is currently being investigated as an antibacterial agent in both microscale and nanoscale formulations. ZnO exhibits significant antimicrobial activities when particle size is reduced to the nanometer range, then nano-sized ZnO can interact with bacterial surface and/or with the bacterial core where it enters inside the cell, and subsequently exhibits distinct bactericidal mechanisms [10] . The interactions between these unique materials and bacteria are mostly toxic, which have been exploited for antimicrobial applications such as in food industry. Interestingly, ZnO-NPs are reported by several studies as non-toxic to human cells [14], this aspect necessitated their usage as antibacterial agents, noxious to microorganisms, and hold good biocompatibility to human cells [12]. The various antibacterial mechanisms of nanomaterials are mostly attributed to their high specific surface area-to-volume ratios [15], and their distinctive physicochemical properties. However, the precise mechanisms are yet under debate, although several proposed ones are suggested and adopted. Investigations on antibacterial nanomaterials, mostly ZnO-NPs, would enhance the research area of nanomaterials, and the mechanisms and phenomenon behind nanostructured materials.

Fashionable materials of therapeutic importance have always been a great interest in nanotechnology world. Tailoring nanomaterials as per specific needs have outranged their use in wider backgrounds[16]. Biofunctional nanoparticles have emerged and gained huge importance due to their super special applications among which metallic based nanoparticles are the key players. Current biomedical and engineering demands have been answered with key innovations based on nanoparticles [17] . Apart from feasibility in altering their chemical properties for specific use, nanoparticle of metal or their oxides withstand rigorous processing conditions that makes them too attractive segment in nanotechnology research fields[18] . Nanotechnology is the manipulation of matter on a molecular scale, which has revolutionised the modern medicine[19.]

ZINC OXIDE NANOPARTICLES

ZnO is described as a functional, strategic, promising, and versatile inorganic material with a broad range of applications. It is known as II–VI semiconductor [20] , since Zn and O are classified into groups two and six in the periodic table, respectively. ZnO holds a unique optical, chemical sensing, semiconducting, electric conductivity, and piezoelectric properties [21]. It is characterised by a direct wide band gap (3.3 eV) in the near-UV spectrum, a high excitonic binding energy (60 meV) at room temperature [22,23,24], and a natural n-type electrical conductivity [25] . These characteristics enable ZnO to have remarkable applications in diverse fields [23]. The wide band gap of ZnO has significant effect on its properties, such as the electrical conductivity and optical absorption. The excitonic emission can persevere higher at room temperature [24] and the conductivity increases when ZnO doped with other metals [22] . Though ZnO shows light covalent character, it has very strong ionic bonding in the Zn–O. Its longer durability, higher selectivity, and heat resistance are preceded than organic and inorganic materials[12] . The synthesis of nano-sized ZnO has led to the investigation of its use as new antibacterial agent. In addition to its unique antibacterial and antifungal properties, ZnO-NPs possess high catalytic and high photochemical activities. ZnO possesses high optical absorption in the UVA (315–400 nm) and UVB (280–315 nm) regions which is beneficial in antibacterial response and used as a UV protector in cosmetics [26].

Zinc oxide has innate antibacterial properties. In the form of nanoparticles, it shows significantly higher antibacterial activity due to increased surface/volume ratio[27]. Studies have shown that zinc oxide can inhibit acid production by Streptococcus mutans and Lactobacillus in dental plaque[28]. Moreover, it has confirmed antibacterial effects on Gram-negative and Gram-positive bacteria and is commonly used as an antibacterial agent in dental hygiene products such as toothpastes and mouthwashes[29]. The purpose of this study was to assess the effect of adding zinc oxide Among all the existing metal oxide nanoparticles, zinc oxide (ZnO) is a mineral zincite that is bio-safe, biocompatible with proven strong anti-bacterial properties, which can powerfully resist broad range of microorganisms due to their ability to generate reactive oxygen species (ROS) on the surface of oxides[30]. ZnO has wider applications in the fields of magnetic, gas sensing, optical and even in piezoelectric[31]. The zincite due to its, strong adsorption ability and large catalytic efficiency it is commonly used in the large scale manufacture of ceramics, pharmaceutical excipients, pigments, sunscreens lotions, in anti fungal preparations and even in physical phenomenon of wastewater and rubber treatment as well [27,28,29].

ZINC OXIDE NANOPARTICLES IN DENTISTRY.

Dental caries is a common infectious disease, in which enamel and dentin are demineralised due to the acids produced from the fermentation of carbohydrates by acidogenic bacteria. At present, carious teeth are commonly restored with tooth-coloured restorative materials such as composite resins due to their optimal aesthetic properties. Occurrence of secondary caries is the most important reason for replacement of composite restorations. Nanotechnology is the manipulation of matter on a molecular scale, which has revolutionised the modern medicine. Zinc oxide has innate antibacterial properties. In the form of nanoparticles, it shows significantly higher antibacterial activity due to increased surface/volume ratio6. Studies have shown that zinc oxide can inhibit acid production by Streptococcus mutans and Lactobacillus in dental plaque. Moreover, it has confirmed antibacterial effects on Gram-negative and Gram-positive bacteria and is commonly used as an antibacterial agent in dental hygiene products such as toothpastes and mouthwashes.

Effects of Zinc Oxide Nanoparticles in Conventional Glass Ionomer Cement

Secondary caries is one of the primary causes for failure of dental restorations. The recognition of fewer incidences of recurrent caries around the silicate restorations and its attribution to fluoride led to the incorporation of fluoride into a number of dental restorative materials. Glass-ionomer cement (GIC) was invented by Wilson and Kent at the Laboratory of the Government Chemist in 1972. These materials are water-based cements known as polyalkenoate cements. Their generic name is based on the reaction between silicate glass and polyacrylic acid, and the formation arises from an acid/base reaction between the components. These cements are translucent and adhesive to tooth structure.

Glass-ionomer cements have unique properties such as biocompatibility, anticariogenic action and adhesion to moist tooth structure. In addition, the coefficient of thermal expansion for glass ionomers is low and close to the values of tooth structure[32] . Although fluoride has been known for many decades to be antimicrobial, there has been little understanding of its precise effects on cells or of the mechanisms that might be used by organisms to overcome this toxicity. Few bacteria have evolved numerous strategies to alleviate the toxic effects of fluoride ions [33.]

Several attempts in developing GIC with enhanced antibacterial effects by addition of agents, such as, chlorhexidine hydrochloride [34], cetyl pyridinium chloride, cetrimide, benzalkonium chloride and titanium oxide nano particles have been reported in the literature[35] The most appropriate choice of antibacterial agents to combine with GIC would be nanoparticles that have proven to be useful in clinical dentistry, and are the ones that do not disturb the mechanical properties. Cationic disinfectants have been investigated both in-vitro and in-vivo for their antibacterial effects against various microorganisms. Literature reveals that titanium oxide is the only nanoparticle that has been widely incorporated in GIC and studies have shown an increase in the antibacterial effects in in- vitro study.

In recent years nanotechnology has permitted the development of new properties of materials. Zinc oxide nanoparticle has been effective against wide range of gram negative and gram positive bacteria [36]. Recent studies have shown that these nano particles have selective toxicity to bacteria but exhibit minimal effects on human cell . However there is lack of studies on antimicrobial behaviour of zinc oxide nanoparticles incorporated into glass ionomer cement. In an approach to enhance the antibacterial potential of conventional glass ionomer cement, zinc oxide nanoparticles were incorporated into conventional GIC and its antibacterial properties, compressive and shear bond strength were investigated their. Hence, the aim of the study was to evaluate the antibacterial and selective mechanical properties of glass ionomer cements containing zinc oxide nanoparticles.

Zinc oxide nanoparticles an antimicrobial filler content for composite resins

The main cause of secondary caries is the accumulation of dental plaque on the surface of dental restorative materials, resulting in the need of replacement of restorations[37]. The use of nano and microparticles to modify dental restorative materials have been grown and researches are focused in development of a restorative material resistant to bacterial accumulation[38]. The incorporation of metal oxides is one of the approaches that have been used to achieve antibacterial activity into the resin-based restorative materials[39]. It was previously demonstrated that nanoparticles of zinc oxide (ZnO) have a broad antimicrobial spectrum [40], and they have been used successfully to modify resin based restorative materials, leading to a reducing of bacterial biofilms on the surface of this materials. This high antimicrobial capacity could be attributed to their size and high surface area. However, smallness in itself is not the goal, the use of different methods of synthesis in order to obtain novel physicochemical properties are also relevant variables affecting antibacterial activity[41]. The shape of particles have been described as an important role in the reactive oxygen species production and antibacterial activity[41]. In this way, the rods and wires of ZnO have demonstrated better results than spherical particles. The antibacterial activity of different shapes of ZnO, such as nanorods, microrods, nanospheres, microspheres, and microflowers, have been reported[42]. Since ZnO presents a wide range of shapes [40] and its antibacterial capacity is shape-dependent[41], ZnO morphology has become a determinant factor in the choice of this material in nano and microscale to modify composite resins. This can be achieved by controlling of parameters such as pH, temperature, solvents, precursor types and physicochemical settings of synthesis. Although the incorporation of ZnO in composite resin can impart antibacterial activity, physical and mechanical properties can be drastically affected and this should be controlled taking into consideration the size, quantity, color, and opacity of particles. Since the physical parameters of particles are directly related to their properties and can influence the particle-microorganism interaction, it is interesting to analyze the properties of a composite resin modified by ZnO microstructures with three dimensional morphology and controlled chemical-physical characteristics. In this way, the aim of this study was to synthesize and characterize microrods and hollow microrods of ZnO, insert it into a composite resin and evaluate its mechanical and antibacterial properties in order to obtain a novel restorative material with antibacterial capacity, increasing the longevity of restorations and its clinical acceptance.

Hardness Improvement of Dental Amalgam Using Zinc Oxide nanoparticles

Dental amalgam has been used in mouth as a permanent dental restorative material since long time ago. Appearing almost indestructible, it always seems to pull through, no matter how it is mistreated. Amalgam, a mixture of mercury with at least one other metal, is chosen due to its low cost, easy application, high strength and durability [43]. Recently, many problems have been faced in dentistry for the usage of amalgam containing excess mercury that simply becomes the cause of illnesses and brings pollution to the environment. A new type of dental amalgam currently being used constitutes less mercury when amalgamated in the correct ratio. In aesthetics view, metallic colour is not well-blended with the natural tooth colour [44,45]. This is where the incorporation of zinc oxide nano powders into the mixture of the new dental amalgam becomes important. Zinc oxide is naturally white and its incorporation into this new dental amalgam might fade the metallic colour of the conventional amalgam out. However, the addition of zinc oxide was primarily intended to improve the hardness of that material. Microparticles and fibers can also be used to reinforce dental resin-based composites. By adding a small amount of short or networked fiber to the composite, a modest increase in strength was proven.

Zinc oxide (ZnO) is a unique material that has prompted an enormous number of researches. Various morphologies and sizes of ZnO materials have led to a wide range of promising applications, such as additive in the production of paints, ceramics, catalysts, electronics, optoelectronics and many more. These unique nano-structures clearly demonstrate that ZnO probably has the richest family of nanostructures of all materials, both in structures and in properties. Various ZnO nanostructures with different morphology such as nanorods, nanotubes, nano- spheres and many more have been found [46]. Meanwhile, properties of ZnO nanomaterial powders are dependent on their micro structural and morphological characteristics, which may vary according to the selected method of synthesis.

Due to a wide range of applications in engineering and biomedical areas, aluminium oxide has become one of the most versatile ceramic oxides employing unique properties such as high elastic modulus, thermal and chemical stability, high strength and toughness -thus enabling it to tremendously perform under tension or bending conditions. A lot of efforts using various methods have been put on synthesizing one-dimensional Al2O3 nanostructure with different morphologies including nanowires, nanoribbons, nanorods, nanofibres and nanotubes [47]. The temperature at above 1200 °C, however, has been used in synthesizing alu- mina nanostructures. It triggers the need to synthesize this material at low tem- perature by using simple techniques. In this regard, this work premise deals with only zinc oxide nanoparticles as filler.

Nanopowders are produced by a wide number of synthesis methods such as self-combustion, sol–gel, hydrothermal, precipitation and oxidation. In combustion synthesis, the high temperature means that only coarse nano-size particles greater than 100 nm can be produced. The sol–gel process being at low temperature conversely offers the greatest scope for the smallest nanosize material.

The final product may be ensured to possess high homogeneity and fine grain size. The actual reaction takes a few hours and other steps such as calcination are split into separate operations of a few hours on each. Realizing the quality of the nano- powders produced by the sol–gel method, the study is done on synthesizing ZnO nanoparticles by sol–gel method and investigates the addition of ZnO as nanofiller to improve mechanical strength of the dental amalgam.

Mechanical and Physicochemical Properties of Newly Formed ZnO-PMMA Nanocomposites for Denture Bases

With the aging of the population, the demand for prosthetic treatment in the stomatognathic system is growing [48]. In toothlessness or multiple teeth deficiencies, removable appliances with an extensive base are still the most common prosthetic solution. The force released in the act of chewing is completely passed by the prosthesis base onto the mucous membrane, the periosteum and bone. This creates the need for taking over by mucosa non-physiological functions, which results in its impaired physiology and increased susceptibility to infection. From the clinical point of view, methacrylate (PMMA) has acceptable mechanical properties, nevertheless attempts have still been made to modify the material so that it would become resistant to microbial adhesion. Some very promising nanoparticles (NPs) that can be used to modify the biomaterial for denture bases are zinc oxide (ZnO) NPs. Zinc oxide is a multi-functional material being a II-VI semiconductor [49]. Properties such as wide band gap (~3.37 eV) or high exciton binding energy (~60 meV) make it an attractive material for electronics and optoelectronics [50,51]. The antibacterial and antifungal activity of ZnO-NPs was the major rationale for commencing in 2014 the research on dentures modified by ZnO-NPs, which are supposed to ultimately be characterized by antifungal properties. At present, this issue has gained a growing interest among the scientist around the world and has already been investigated by several research groups.

The basic property decreasing the deposition of food debris is the smoothness of the surface expressed by its roughness. A smaller expansion of the surface results in a reduced number of natural niches for C. albicans, which considerably hampers the formation of the fungal biofilm structure .The hardness of the material does not directly affect the deposition of pathogens but becomes an exponent of the resistance supplement to mechanical damage[52]. It occurs during the act of chewing but also during the performance of denture hygiene especially when the patient, against medical advice, uses a substance with a high abrasion index. This can lead to the micro damage of prostheses and thereby increases the roughness parameter. Another property that affects the deposition of microorganisms is hydrophobic or hydrophilic nature of the surface. With the increase in hydrophilic property the biofilm formation is reduced [53]. It is believed that the hydrophilic material interferes with the initial phase of microbial adhesion based on electrostatic interactions, Van der Waals forces and hydrogen interactions. Candida species have a very strong affinity to the surface of the acrylic base due to its specific nature but also because of its hydrophobic properties. In the cell wall of Candida there are adhesins, mainly mannoproteins, responsible for adhesion to host cells. Formosa et al. have shown that depending on the conditions fungal cells can produce adhesins on their surface. Then they change the conformation of structures known as nano domains, exhibiting hydrophobic properties and giving fungi affinity to all hydrophobic, abiotic surfaces, including acrylic resin material. Absorbability of the material is also its negative feature. In the first stage of denture use the material absorbs fluids from the oral cavity to its interior. This results in an increase in weight of the material, which does not significantly affect the retention and function of the prosthesis but the liquid absorbed into the interior comprises microorganisms present in the saliva making formation of the fungal biofilm possible . However, some authors do not notice the correlation between the sorption of water and ease of accumulation of microorganisms. The PMMA porosity, regarded as one of the major causes of the biofilm formation, seems to be of minor importance. Studies conducted by Osica et al. on the basis of computed tomography revealed an average porosity of PMMA at 0.01%. However, it should be remembered that this parameter varies over time, depending on the length of the prosthesis use and at a later stage it can play a role in the deposition of microorganisms. The process of biofilm formation and the mechanisms responsible for this process are multi-faceted and are the subject of interest to scientists all around the world.

The effect of ZnO nanoparticle coating on the frictional resistance between orthodontic wires and ceramic brackets

Tooth movement is an essential part of orthodontic treatment. Sliding the tooth on an orthodontic wire is one of the techniques in this context, with advantages including a decrease in chair time, patient comfort and 3-dimensional control of tooth movements.[54] On the other hand, one of the major disadvantages of this technique is the wire-bracket friction, requiring application of higher forces to overcome it, which endangers the anchorage.[55] In order to induce tooth movements, it is necessary to apply mechanical forces in the range of 100–200 g on the tooth. Friction between the wire and bracket, which opposes tooth movement, is associated with sliding movements. Subsequent to application of forces on the tooth, tipping movements begin, creating an angle between the bracket and the wire. When such an angle reaches a threshold, a contact is created between the wire and bracket margins, resulting in adhesion between metallic surfaces. Then, the wire gradually undergoes notching and plastic deformation. All these phenomena, in turn, prevent continuous tooth movements, leading to intermittent halts in tooth movement.To overcome such a problem, the applied force should increase up to 40–60% of the initial force. On the other hand, any increase in the amount of applied force increases the risk of anchorage loss, which is considered an unfavorable event in orthodontic treatment. In addition, an increase in the amount of force increases the risk of root resorption.[56] At present the use of ceramic brackets which are more esthetic than steel brackets is on the increase but these brackets exhibit significantly higher frictional resistance compared to steel brackets. Differences in frictional resistance between steel and ceramic brackets are attributed to the surface characteristics of ceramic brackets.6

Use of nanoparticles with spherical structure was introduced in 1990s as solid lubricants. This technological achievement has been considered to decrease friction between metallic surfaces. Redlich et al8 evaluated the amount of decrease in frictional forces between stainless steel orthodontic brackets and wires after covering the wires with saturated nickel-phosphorus and tungsten disulfide nanoparticles. The results showed a significant decrease in frictional forces of the samples. Samorodnitzky et al[57] evaluated the effect of depositing spherical tungsten sulfide (WS2) nanoparticles on decreasing friction in nickel titanium (NiTi) orthodontic wires. The results showed that WS2-containing wires exhibited a significant decrease in friction in all the three tests; even AFM(atomic force microscope) analysis showed [56,58] folds of decrease in frictional forces in wires containing WS2 compared to wires with no coating. In a study by Wei et al,10 depositing a nanolayer of CNx (a carbon nitride film) on the stainless steel wires resulted in a decrease in friction. Goto et al11 showed that depositing ZnO particles on stainless steel substrate in vacuum decreased friction. Prasad et al[59] reported that depositing WS2 particles on Iconel (a family of austenite nickel chromium-based super alloys) substrate resulted in a decrease in friction and adding ZnO increased these effects several folds. Katz [60] showed that WS2 nanoparticles significantly decreased friction in arch wires. Obviously, future clinical use of coated wires, brackets or both of them will depend on using safe biocompatibility materials according to accepted procedures. In particular, zinc oxide has been used in many areas, such as catalysis, gas sensors, and recently as lubricants.

CONCLUSION:

This review emphasises on the use of zinc oxide nanoparticles in various aspects of dentistry. Most of the reports have shown more research and study has to be carried on zinc oxide Nano particles to incorporate it commonly in today's practice.

REFERENCES:

[1] S. Sahoo, Socio-ethical issues and nanotechnology development: perspectives from India, in 2010 10th IEEE Conference on Nanotechnology (IEEE-NANO), Seoul, South Korea, USA, 17–20 August 2010 (IEEE, 2010), pp. 1205–1210. doi:10.1109/NANO.2010.5697887

[2] V. Yadav, Nanotechnology, big things from a tiny world: a review. AEEE 3(6), 771–778 (2013)

[3] S. Pal, Y.K. Tak, J.M. Song, Does the antibacterial activity of silver nanoparticles depend on the shape of the nanoparticle? A study of the gram-negative bacterium Escherichia coli. Appl. Environ. Microbiol. 73(6), 1712–1720 (2007). doi:10.1128/AEM.02218-06

[4] B. Ashe, A Detail investigation to observe the effect of zinc oxide and Silver nanoparticles in biological system, M.Sc. (Roll NO-607bm004), National Institute of Technology, 2011

[5] C. Buzea, I.I. Pacheco, K. Robbie, Nanomaterials and nanoparticles: sources and toxicity. Biointerphases 2(4), MR17MR71 (2007). doi:10.1116/1.2815690

[6] J.W. Rasmussen, E. Martinez, P. Louka, D.G. Wingett, Zinc oxide nanoparticles for selective destruction of tumor cells and potential for drug delivery applications. Expert Opin. Drug Deliv. 7(9), 1063–1077 (2010). doi:10.1517/17425247.2010.502560

[7] R. Brayner, R. Ferrari-Iliou, N. Brivois, S. Djediat, M.F. Benedetti, F. Fie´vet, Toxicological impact studies based on Escherichia coli bacteria in ultrafine ZnO nanoparticles colloidal medium. Nano Lett. 6(4), 866–870 (2006). doi:10.1021/nl052326h

[8] N. Jones, B. Ray, K.T. Ranjit, A.C. Manna, Antibacterial activity of ZnO nanoparticle suspensions on a broad spectrum of microorganisms. FEMS Microbiol. Lett. 279(1), 71–76 (2008). doi:10.1111/j.1574-6968.2007.01012.x

[9] R. Jalal, E.K. Goharshadi, M. Abareshi, M. Moosavi, A. Yousefi, P. Nancarrow, ZnO nanofluids: green synthesis, characterization, and antibacterial activity. Mater. Chem. Phys. 121(1), 198–201 (2010). doi:10.1016/j.matchemphys.2010.01.020

[10] J.T. Seil, T.J. Webster, Antimicrobial applications of nanotechnology: methods and literature. Int. J. Nanomed. 7, 27672781 (2012). doi:10.2147/IJN.S24805

[11] Z. Emami-Karvani, P. Chehrazi, Antibacterial activity of ZnO nanoparticle on gram-positive and gram-negative bacteria. Afr. J. Microbiol. Res. 5(12), 1368–1373 (2011)

[12] N. Padmavathy, R. Vijayaraghavan, Enhanced bioactivity of ZnO nanoparticles—an antimicrobial study. Sci. Technol. Adv. Mater. 9(3), 035004 (2008). doi:10.1088/1468-6996/9/3/035004

[13] K.R. Raghupathi, R.T. Koodali, A.C. Manna, Size-dependent bacterial growth inhibition and mechanism of antibacterial activity of zinc oxide nanoparticles. Langmuir 27(7), 4020–4028 (2011). doi:10.1371/journal.pone.0085981

[14] G. Colon, B.C. Ward, T.J. Webster, Increased osteoblast and decreased Staphylococcus epidermidis functions on nanophase ZnO and TiO2. J. Biomed. Mater. Res. 78(3), 595–604 (2006). doi:10.1002/jbm.a.30789

[15] J.T. Seil, E.N. Taylor, T.J. Webster, Reduced activity of Staphylococcus epidermidis in the presence of sonicated piezoelectric zinc oxide nanoparticles, in 2009 IEEE 35th Annual Northeast Bioengineering Conference, Boston, MA, USA, 3–5 April 2009 (IEEE, 2009), pp. 1–2. doi:10.1109/NEBC.2009. 4967674

[16] Wood, J., 2008. The top ten advances in materials science. Mater. Today, 11: 40-45.

[17] Ng, L.Y., A.W. Mohammad, C.P. Leo and N. Hilal, 2013. Polymeric membranes incorporated with metal/metal oxide nanoparticles: A comprehensive review. Desalination, 308: 15-33.

[18] Niederberger, M. and N. Pinna, 2009. Metal Oxide Nanoparticles in Organic Solvents: Synthesis, Formation, Assembly and Application. Springer-Verlag, London.

[19] Rajalakshmi, M., A.K. Arora, B.S. Bendre and S. Mahamuni, 2000. Optical phonon confinement in zinc oxide nanoparticles. J. Applied Phys., 87: 2445-2448.

[20] Y.G. Gertrude Neumark, I. Kuskovsky, in Springer Handbook of Electronic and Photonic Materials: Doping Aspects of Zn-Based Wide-Band-Gap Semiconductors, ed. by P.C. Safa Kasap (Springer, 2007), pp. 843–854. doi:10.1007/978-0-387-291857_35 18. Z.

[21] Fan, J.G. Lu, Zinc oxide nanostructures: synthesis and properties. J. Nanosci. Nanotechnol. 5(10), 1561–1573 (2005). doi:10.1166/jnn.2005.182

[22] Z.L. Wang, Zinc oxide nanostructures: growth, properties and applications. J. Phys.: Condens. Matter 16(25), R829–R858 (2004). doi:10.1088/0953-8984/16/25/R01 20.

[23] Z.L. Wang, J. Song, Piezoelectric nanogenerators based on zinc oxide nanowire arrays. Science 312(5771), 242–246 (2006). doi:10.1126/science.1124005 21.

[24] A. Janotti, C.G. Van de Walle, Fundamentals of zinc oxide as a semiconductor. Rep. Prog. Phys. 72(12), 126501 (2009). doi:10. 1088/0034-4885/72/12/126501

[25] J. Wellings, N. Chaure, S. Heavens, I. Dharmadasa, Growth and characterisation of electrodeposited ZnO thin films. Thin Solid Films 516(12), 3893–3898 (2008). doi:10.1016/j.tsf.2007.07.156

[26] Z. Song, T.A. Kelf, W.H. Sanchez, M.S. Roberts, J. Ricka, M. Frenz, A.V. Zvyagin, Characterization of optical properties of ZnO nanoparticles for quantitative imaging of transdermal transport. Biomed. Opt. Express 2(12), 3321–3333 (2011). doi:10.1364/BOE.2.003321

[27] Kasraei S, Sami L, Hendi S, AliKhani M-Y, Rezaei-Soufi L, Khamverdi Z. Antibacterial properties of composite resins incorporating silver and zinc oxide nanoparticles on Streptococcus mutans and Lactobacillus. Restor Dent Endod. 2014 May;39(2):109-14. doi: 10.5395/rde.2014.39.2.109.

[28] Hirota K, Sugimoto M, Kato M, Tsukagoshi K, Tanigawa T, Sugimoto H. Preparation of zinc oxide ceramics with a sustainable antibacterial activity under dark conditions. Ceramics International. 2010 Mar;36(2):497-506. doi:10.1016/j.ceramint.2009.09.026.

[29] Osorio R, Yamauti M, Osorio E, Ruiz-Requena M, Pashley DH, Tay F, et al. Zinc reduces collagen degradation in demineralized human dentin explants. J Dent. 2011 Feb;39(2):148-53. doi: 10.1016/j.jdent.2010.11.005.

[30] Sawai J. Quantitative evaluation of antibacterial activities of metallic oxide powders (ZnO, MgO and CaO) by conductimetric assay. J Microbiol Methods. 2003;54(2):177-82.

[31] Dumont VC, Silva RM, Almeida-Júnior LE, Roa JPB, Botelho AM, Santos MH. Characterization and evaluation of bond strength of dental polymer systems modified with hydroxyapatite nanoparticles. J Mater Sci Chem Eng. 2013 Dec;1(7): 13-23. doi: 10.4236/msce.2013.17003.

[32] Mohanavelu Deepalakshmi, Saravanan Poorni, Revathi Miglani, Indira Ramachandran. Evaluation of the antibacterial and physical properties of glass ionomer cements containing chlorhexidine cetrimide: An in-vitro study. Ind J Dent Res 2010, 21(4) 552-6.

[33] Jenny L. Baker, Narasimhan Sudarsan, Zasha Weinberg, Adam Roth, Randy B. Stockbridge, and Ronald R. Breaker.. Widespread Genetic Switches and Toxicity Resistance Proteins for fluoride. Science 2012; 335(6065):233-5.

[34] Yesilyurt C, Er K, Tasdemir T, Buruk K, Celik D, Antibacterial Activity and Physical Properties of Glass-ionomer Cements Antibiotics, Oper Dent. 2009;34(1):18-23.

[35] Elsaka SE, Hamouda IM, Swain MV. Titanium dioxide nanoparticles conventional addition glass-ionomer Influence on physical and antibacterial properties, J Dent. 2011;39(9): 589–98.

[36] Jones N, Ray B, Ranjit KT, Manna AC. Antibacterial activity of ZnO nanopar-ticle suspensions on a broad spectrum of microorganisms. FEMS Microbiology Letters 2008;279:71–76..

[37] Burke, F. J., Crisp, R. J., Bell, T. J., Healy, A., Mark, B., McBirnie, R., & Osborne-Smith, K. L. (2001). One-year retrospective clinical evaluation of hybrid composite restorations placed in United Kingdom general practices. Quintessence International, 32, 293–298.

[38] Gjorgievska, E., Tendeloo, G. V., Nicholson, J. W., Coleman, N. J., Slipper, L. J., & Booth, S. (2015). The incorporation of nanoparticles into conventional glass-ionomer dental restorative cements. Microscopy and Microanalysis, 21, 392–406.

[39] Wang, Z., Shen, Y., & Haapasalo, M. (2014). Dental materials with antibiofilm properties. Dental. Materials, 30,e1–e16.

[40] Raghupathi, K. R., Koodali, R. T., & Manna, A. C. (2011). Size-dependent bacterial growth inhibition and mechanism of antibacterial activity of zinc oxide nanoparticles. Langmuir, 27, 4020–4028.

[41] Pal, S., Tak, Y. K., & Song, J. M. (2007). Does the antibacterial activity of silver nanoparticles depend on the shape of the nanoparticle? a study of the Gram-negative bacterium Escherichia coli. Applied Environmental Microbiology, 73, 1712–1720.

[42] Rago, I., Chandraiahgari, C. R., Bracciale, M. P., De Bellis, G., Zanni, E., Guidi, M. C., ...Uccelletti, D. (2014). Zinc oxide microrods and nanorods: different antibacterial activity and their mode of action against Gram-positive bacteria. RSC Advances, 4, 56031–56040.

[43] Abu Kassim, N.H., Yahya, N.A., Radzi, Z., Basirun, W. J., Ghani, A.A.: Silverfil: Its physical characterization, 3rd Kuala Lumpur international conference on biomedical engineering 2006 Biomed, Kuala Lumpur, Malaysia, 11–14 Dec 2006

[44] Trevor Burke, F.J.: Amalgam to tooth-coloured materials—implications for clinical practice and dental education: governmental restrictions and amalgam-usage survey results. J. Dent. 32, 343–350 (2004)

[45] Bedini, R., Chistolini, P., De Angelisa, G., Albergob, G.F.: Mechanical performance of dental amalgam-composite interfaces. Clin. Mater. 17, 147–150 (1994)

[46] Kharisov, B. I.: A Review for synthesis of nanoflowers, Recent Patents on Nanotechnology, 000-000, vol. 2 (2008)

[47] Shah, M.A., Kumar, J.: Synthesis and characterization of a-Al2O3 nanorods prepared by a simple aluminum-water reaction. Afr. Phys. Rev. 2, 0005 (2008)

[48] Konopka, T.; Dembowska, E.; Pietruska, M.; Dymalski, P.; Górska, R. Periodontal status and selected indexes of oral cavity condition in Poles aged 65 to 74 years. Epidemiol. Rev. 2015, 69, 643–647.

[49] Fortunato, E.; Gonçalves, A.; Pimentel, A.; Barquinha, P.; Gonçalves, G.; Pereira, L.; Ferreira, I.; Martins, R. Zinc oxide, a multifunctional material: From material to device applications. Appl. Phys. 2009, 96, 197–205.

[50] Klingshirn, C.F.; Waag, A.; Hoffmann, A.; Geurts, J. Zinc Oxide, 1st ed.; Springer: Berlin, Germany, 2010; ISBN 978-3-642-10576-0.

[51] Ozgur, U.; Hofstetter, D.; Morkoc, H. 2010 ZnO devices and applications: A review of current status and future prospects. Proc. IEEE 2010, 98, 1255–1268.

[52] Cierech, M.; Szczypi´nska, A.; Wróbel, K.; Goła´s, M.; Walke, W.; Pochrz ̨ast, M.; Przybyłowska, D.; Bielas, W. Comparative analysis of the roughness of acrylic resin materials used in the process of making the bases of dentures and investigation of adhesion of Candida albicans to them. Dent. Med. Probl. 2013, 50, 341–347.

[53] Azevedo, A.; Machado, A.L.; Vergani, C.E.; Giampaolo, E.T.; Pavarina, A.C. Hardness of denture base and hard chair-side reline acrylic resins. J. Appl. Oral Sci. 2005, 291–295.

[54] Bednar JR, Gruendeman GW, Sandrik JL. A comparative study of frictional forces between orthodontic brackets and arch wires. Am J Orthod Dentofacial Or- thop1991;100(6):513-522.doi:10.1016/0889-5406(91)70091- A

[55] Nikolai RJ. Bioengineering Analysis of Orthodontic. 1st ed. Philadelphia: Lea and Febiger;1982.p.131-55.

[56] Angolkar PV, Kapila S, Duncanson MG Jr, Nanda RS. Eval- uation of friction between ceramic brackets and orthodontic wires of four alloys. Am J Orthod Dentofacial Orthop 1990;98(6):499-506.

[57] Samorodnitzky Naveh GR, Redlich M, Rapaport L, Feldman Y, Tenne R. Inorganic fuullerne – like tungsten disulfide na- nocoating for friction reduction of nickel-titanium alloys. Nanomed 2009;4(8):943-50. doi: 10.2217/nnm.09.68

[58] Thorstenson GA, Kusy RP .Resistance to sliding of self- ligating brackets versus conventional stainless steel twin brackets with second-order angulation in the dry and wet (sa- liva) states. Am J Ortod Dentofacial Orthop 2001;120(4):361-70. doi:10.1067/mod.2001.116090

[59] Prasad SV, McDevit NT, Zabinsky JS. Tribology of tungstan disulfide-nanoccrystalline zinc oxide adaptive lubricant film from ambient to 500°C. Wear 2000; 237(2):186-96. doi:10.1016/S0043-1648(99)00329-4

[60] Katz A, Redlich M, Rapoport L, Wagner HD, Tenne R.Self- lubricating coatings containing fullerene-like WS2 nanopar- ticles for orthodontic wires and other possible medical appli- cations. Tribol Lett 2006; 21(2):135-9.doi: 10.1007/s11249- 006-9029-4