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RESEARCH ARTICLE

Exploring the Potential of Electrospun Polymers for High-Performance Dental Composite: A Mini Review

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Abstract

Dental resin composite is the most common material used in dentistry. Resin composite refers to combination of two or more materials that typically consists of matrix polymers, fillers, and a coupling agent. Fillers are essential in composites, as their presence significantly improves the material's hardness. However, beside its excellent mechanical properties, Resin composite also has several limitations, including polymerization shrinkage, high coefficient of thermal expansion, and low wear resistance. Adding reinforcement materials such as electrospun fiber to composite fillers has shown improvement of its mechanical properties. Electrospun fiber refers to a fiber that produced through electrospinning methods. There are various types polymers used in electrospinning fabrication, such as Poly (methyl methacrylate) (PMMA), Polyacrylonitrile (PAN), Polyether ether ketone (PEEK), Polyvinyl alcohol (PVA), Polycaprolactone (PCL), and Polylactic acid (PLA). The electrospinning method utilizes a high-voltage electrical source applied to this polymer solution. Electrical voltage will initiate the formation of droplets that then elongate to form fibers. Electrospun fibers have versatile applications in dentistry and can be used as a reinforcing agent for dental composite restorations. Therefore, electrospun fibers has a lot of promising potential in dentistry, as they can produce materials with excellent mechanical properties by using a simple and efficient method.

Keywords: Electrospun polymer, dental composite, reinforced material

1. Introduction

Resin composites have been commonly used as dental restorative materials for almost 50 years. The first introduction of resin composites in history dates back to around 1950–1960 [1], [2]. Dental resin composites are now the most widely used materials in dental restorations, surpassing conventional amalgam restorations due to their excellent mechanical properties and aesthetic appearance, which closely resemble natural teeth [3], [4], [5], [6]. Besides their superior mechanical properties, there are also several limitations including polymerization shrinkage, high coefficient of thermal expansion, and low wear resistance [1], [7], [8]. To overcome this limitation, polymer-based fiber can be used as a reinforced material for dental composite. Polymers with fiber-based reinforcement are known for their significant improvements like excellent stabilities [9], [10], [11].

The current advancements in nanotechnology offer possibilities to modify dental materials on a nanoscale, enhancing the opportunity to fabricate nanofibers that can be used as reinforcement agents in dental composite restorations [12]. According to *Ramakrishna et al*, there are various methods for producing nanofibers, such as drawing techniques, template synthesis, phase separation, self-assembly, and electrospinning [13]. Among these techniques, electrospinning provides more benefits considering several aspect such as low-cost, highly efficient, and requires only a simple procedure. Electrospun nanofibers hold significant potential in dentistry by producing materials with excellent mechanical and functional properties [14], [15], [16].

2. Materials and Methods

The methodology used for this article is a narrative review. The narrative review will provide a descriptive overview of various polymer fibers that are commonly used in the electrospinning method as a reinforcement agents for dental composites. The review will be written from a theoretical and contextual perspective. Section 3 of this article will provide a brief overview of resin composites and their applications in the dental field. The choice of polymers that can be used as potential reinforcement agents for dental composites will be discussed in section 4. Mechanical properties of fiber reinforced dental composites using various polymers as explained on previous section will be discussed on section 5. The electrospinning process in a brief will be discussed in section 6. Section 7 will discuss about the limitations and future perspectives on the current electrospinning research, also their potential application in dentistry.

3. Resin Composites

A composite refers to a combination of two or more materials with different properties that create a new material with desired functional properties, which can't be achieved by just using a single material [17], [18]. The most common composite configuration in dentistry is usually made from the combination of polymers and ceramics as filler, with polymers used to bond the ceramic particles. Polymers are also used as a matrix in composite and other particles as a reinforcing material. *Polymer matrix composites* usually known as *resin composites,* can be used as a dental sealant, intracoronal and extracoronal temporary restoration, dental veneer, dentures, dental cement, and cores [18]. Resin composites have three main components to build up it structures, which consist of matrix, fillers, and coupling agents. Another component like an inhibitor sometimes can be included to improve the mechanical properties, appearances, and durability of the material [19]. Resin composites usually contain modified methacrylates or acrylates like Bis-GMA (Bisphenol A-Glycidyl Methacrylate). Bis-GMA is continuously used to be the most widely monomer that is used in composite fabrication [20].

Resin composite is usually classified based on their fillers. Filler contributes to be the main component in composite as it holds significant changes to reduce composite's brittleness and improve composite's hardness [17]. Composite fillers can be classified dimensionally by looking at their particle size or geometrically by looking at their morphology [1], [2], [3]. Based on their particle size, composite fillers can be divided into macro-filled, micro-filled, hybrid, blended/modern hybrid, and nano-composites [3], [17]. Also by looking at their morphology, composite fillers can be divided into several classifications such as fibrous filler, particulate filler, and novel-shaped filler [1].

4. Fiber Reinforced Synthetic Polymers

4.1 Poly methyl methacrylate (PMMA)

Poly methyl methacrylate (PMMA), widely known as acrylic, is a transparent thermoplastic polymer which often used in dentistry due to its good biocompatibility and mechanical properties. For dental applications, PMMA is often used as a base for removable orthodontic appliances, dentures, and crown materials in prosthodontic treatments. The addition of materials such as ceramics, metals, and fibers can enhance the hardness of PMMA. Due to its excellent biocompatibility, PMMA is also commonly used in biomedical applications, including scaffolding fabrication, tissue engineering, and bone cement [19], [20], [21]. Moreover, PMMA has been used as a fiber-post material in dentistry [22]. PAN (Polyacrylonitrile)-PMMA nanofibers have also been fabricated through the electrospinning method and used as reinforcement material in composites because the methacryloyl components of PMMA are more likely to bond with the major chains of Bis-GMA as seen on Figure 1. Bis-GMA is a commonly used dimethacrylate in dental composites. Synthesis of PAN-PMMA fiber produces a good quality nanofiber with PMMA as the shell and PAN as the core, some PMMA can dissolve in Bis-GMA monomers and produce a shell that surrounds the core of PAN, which is then called a Semi-IPN-Structures [23].

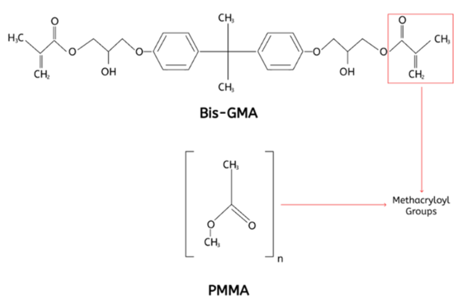

Figure 1. Methacryloyl bond between Bis-GMA and PMMA

4.2 Polyacrylonitrile (PAN)

In previous research by Zhang et al, PAN polymer was reinforced with silica (SiO_2), and synthesized using the electrospinning method. The addition of ceramics like silica with quartz crystals can enhance the hydrophilicity, hardness, and permeability of the material. PAN also has a dielectric constant that is compatible with the electrospinning process [24]. The fabrication of nanofibers with silica fillers has gained significant attention due to their excellent mechanical properties. Silica exists in three crystalline phases: quartz, cristobalite, and tridymite. The hardness of silica in the quartz phase, based on the Mohs Hardness Scale, is 7, which corresponds to a Knoop hardness value of 820. Therefore, silica with a quartz structure possesses the most favorable crystallinity phase [24].

4.3 Polyether ether ketone (PEEK)

Polyether ether ketone (PEEK) is a superior type polymer that is commonly used for implants or as a support material for dentures. PEEK possesses excellent mechanical strength and good thermal stability. However, PEEK is a bioinert material with certain limitations, one of the major examples is its low ability to bond with surrounding tissue during implantation. This limitation results in poor osseointegration with bone and tissue. To address this issue, researchers often modify the surface of PEEK by combining them with other materials through specific methods to enhance osseointegration. This process is also known as surface modification [25], [26]. According to Verma et al, PEEK combined with bioactive particles, such as hydroxyapatite, can improve the development potential of PEEK-based composites [25]. PEEK has an elastic modulus of approximately 3.1 GPa, which is similar to human bone. Additionally, PEEK can be easily modified by reinforcing it with other materials, such as carbon fiber. Reinforcing PEEK with carbon fiber can increase their elastic modulus to approximately 18 GPa, making them a better alternative for dental composites compared to metal-based restorations [27].

4.4 Polyvinyl alcohol (PVA)

Polyvinyl Alcohol) (PVA) is the most common polymer used for the electrospinning method. PVA has so many advantages, it's non-toxic, environmentally friendly, and soluble so it's easy to use as polymers in the electrospinning process. PVA can also stimulate the development of new tissue if it's used for tissue engineering materials. PVA's solubility can be advantageous but on the other hand, this can be their major limitation. When PVA is used for dental applications, they will more likely to dissolve so fast. As a result, the materials will decrease its strength and stability. To overcome this problem, PVA is usually combined with hydrophobic fillers to maintain their solubility [28]. PVA fiber can be used as a reinforcing agent for dental composite restorations. Based on Li et al, electrospun PVA can increase the mechanical properties of dental composites. Adding 0,05% nanofiber PVA to dental composite will obtain its compressive strength up to 30% and also prevent unwanted shrinkage more effectively [29].

4.5 Polycaprolactone (PCL)

Polycaprolactone (PCL) is a low-cost thermoplastic material and is usually used as a polymer for nanofiber fabrication through the electrospinning method. PCL is biodegradable and has been widely used for drug delivery systems. In Dental fields, PCL is commonly used as a supporting material combined with alginate to prevent bacterial accumulation after dental implantation. PCL can also be used as a drug delivery system that incorporates nano-hydroxyapatite and amoxicillin membranes to decrease bacterial contamination of periodontal treatment. Furthermore, PCL has a wide potential for tissue engineering material. PCL combined with bioactive glass filler can enhance cell proliferation along with the mechanical properties of scaffolds. PCL combined with gelatin can also be used as a regenerative agent for periodontal treatment [30].

4.6 Polylactic acid (PLA)

Polylactic Acid (PLA) is a widely used polymer for drug delivery systems and periodontal tissue regeneration. However, PLA can produce acids that may potentially inhibit tissue regeneration. To address this issue, PLA needs to be combined with other materials or fillers when used for tissue regeneration. PLA fibers combined with beta-tricalcium phosphate (β-TCP) have been shown to reduce tissue damage caused by these acidic products. Additionally, a combination of PLA with Metronidazole (MNZ) has been utilized to control bacterial accumulation in the treatment of periodontitis. Furthermore, a combination of PLA, polycaprolactone (PCL), and gelatin incorporating tetracycline has demonstrated significant improvements in preventing the formation of bacterial biofilms that could occur after dental implantation [30].

5. Mechanical Properties of Fiber Reinforced Composites

The mechanical properties of fiber-reinforced composites using PMMA, PAN, PEEK, PVA, PCL, and PLA with electrospinning methods are shown in Table 1, including data from several previous studies.

6. Electrospinning

Resin composites can be modified by adding nano-sized filler particles or nano-sized fibers. Nanofibers produced through electrospinning can yield high-quality Fiber Reinforced Composites (FRCs). Research on fiber fabrication using PAN or PVA polymers has demonstrated improvements in the mechanical properties of the resulting materials, making them suitable as reinforcement for dental composites. Electrospun fibers can also be used as a reinforcement material for dental implants. Dental implants are materials that come into direct contact with bone and support dentures and orthodontic appliances. Various materials, including titanium and alloys, have traditionally been used to enhance the performance of dental implants [15], [36]. More recently, zirconia and advanced reinforced polymers, such as PEEK, have gained attention as alternative reinforcement materials due to their excellent mechanical strength, biocompatibility, and potential to improve the durability and functionality of dental implants [37].

Table 1. Mechanical Properties of Fiber Reinforced Composites

Materials	Mechanical Properties	Applications	References
PMMA-SiO2	132.74 MPa (Flexural Strength)	Dental Composite	[12]
PAN-PMMA	136.3 ± 12.9 MPa (Flexural Strength)	Dental Composite	[31]
PVA-HA-CNT	100.5 ± 5.9 MPa (Compressive Strength)	Dental Composite	[32]
PEEK-PMMA-CF	140.24 ± 14.24 MPa (Compressive Strength)	Bone Implant	[33]
PCL-HA	149.15 ± 16.99 MPa (Young's Modulus)	Nanofibrous coating for titanium implant	[34]
PLA-Chloroform	160.67 ± 34.06 MPa (Young's Modulus)	Tissue engineering scaffold	[35]

6.1 Electrospinning Methods

Electrospinning is a well-known method to produce nanofiber from various polymers. Electrospinning uses an electrostatic force generated from high voltage between positive and negative electrodes [38]. During the electrospinning process, high voltage will be applied to the polymer solution using a syringe needle. High voltage will initiate the droplets which will be formed at the syringe needle's tip. These droplets are induced with an electrical charge applied by a high voltage, causing the polymer solution to be emitted toward the oppositely charged electrode [14]. When a high voltage is applied to the syringe needle, small droplets begin to form at the syringe tip as the flow rate pushes the polymer solution through the syringe pump. These droplets are often referred to as an "orifice". The polymer solution becomes electrically charged due to the applied high voltage, causing it to change shape into a cone, commonly known as a "Taylor cone", due to electrostatic forces. These forces initiate a "jet" from the polymer solution. The jet, carrying an electrical charge, is stretched and bent as it elongates toward the collector. The electrospinning process is illustrated in Figure 2, which shows how a polymer solution in a syringe that applied with a high voltage, can produce nanofibers [39], [40].

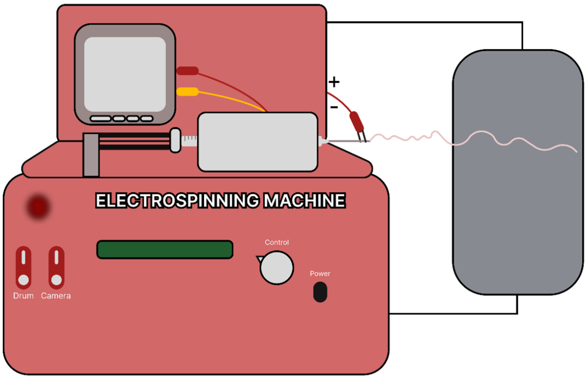

Figure 2. Illustration of the Electrospinning Process

7. Challenges and Future Perspective

Fibers produced through the electrospinning method are influenced by various factors, including solution, processing, and ambient parameters. Solution parameters are typically affected by the concentration, molecular weight, and viscosity of the polymers. The concentration of the polymer solution plays a significant role in determining the size and morphology of electrospun fibers. Nano-sized fibers can be achieved at relatively low concentrations, while higher concentrations may increase fiber diameter due to bead formation.Molecular weight represents the involvement of polymer chains in the solution. Low molecular weight can result in defects and bead formation on the fibers. Low-viscosity solutions help prevent bead formation, but if the viscosity is too high, the solution may be difficult to eject from the syringe tip [40].

Processing parameters, such as voltage, flow rate, collector type, and tip-to-collector distance (TCD), are also crucial in the electrospinning process. According to *Zhang et al*, high voltage can increase the likelihood of bead formation on electrospun fibers. However, *Yuan et al* conclude that high voltage facilitates repulsive forces on the emitted charges, which reduces fiber size. A low flow rate is generally recommended for polymer solutions, as it allows sufficient time for polarization. In contrast, a high flow rate can lead to bead formation and thicker fibers, as the solution may dry before reaching the collector [40].

During electrospinning, the collector acts as a substrate that collects the fibers as they are deposited. Alumunium foil is the most used material for electrospun collectors. However, there are several limitations when using alumunium foil as an electrospun collector, such as difficulty transferring fiber into another substances. Therefore, various electrospun collectors like wire mesh have been developed to exchange aluminium foil. Tip-to-collector distance (TCD) refers to the distance between the collector and the syringe tip in the electrospinning process. If the distance is too short, the electrospun solution may not have enough time to harden before reaching the collector. Conversely, if the distance is too long, bead formation on the electrospun fibers is more likely to occur [14], [40].

Ambient parameters, such as humidity and temperature, also can influence fiber morphology and diameter. According to *Mituppatham et al*, higher temperatures will result in the production of fibers with thinner diameters. Humidity plays an important role as well. Low humidity can cause the solution to dry out, as it increases the evaporation rate and makes the solution more likely to evaporate before reaching the collector. [40]. Proper optimization of these parameters can yield fibers with excellent properties, such as high surface area, porous structures, and suitable elasticity, making them ideal for medical, filtration, drug delivery, and tissue engineering applications [36].

Electrospun nanofibers hold significant potential as reinforcement agents in dental resin composites. The incorporation of nanoscale fillers, whether as nanoparticles or nanofibers, can significantly enhance the mechanical properties of composite materials, improving tensile strength and fracture resistance. Electrospun nanofibers made from polymers such as Poly(methyl methacrylate) (PMMA), Polyacrylonitrile (PAN), or Polyvinyl Alcohol (PVA) have shown promising results in enhancing the mechanical performance of composites. Fiber Reinforced Composites (FRCs) developed through this method exhibit greater flexibility compared to conventional fillers and facilitate more uniform load distribution within the resin matrix [41].

In the future, these nanofibers can be integrated into dental resin composite formulations to strengthen restorative materials such as fillings, inlays, and onlays. The use of electrospun nanofibers as fillers not only enhances the composite's resistance to chewing forces but also makes the material lighter and more biocompatible. Furthermore, the potential of nanofibers to mimic natural tissue structures could play a key role in dental tissue regeneration, making them an innovative solution for creating longer-lasting and more effective restorative materials. As electrospinning technology and related research continue to advance, the use of nanofibers as reinforcement agents in dental resin composites is expected to become a new standard in restorative care, providing stronger and longer-lasting solutions for patients [36], [41].

8. Conclusion

Resin composites have been used widely in dentistry and are preferred over traditional amalgam due to their excellent mechanical property and good natural appearance. However, resin composites have several limitations such as polymerization shrinkage and low wear resistance, to overcome these limitations, polymer-based composites with fiber reinforcement can be used to enhance the quality of the materials. Nanotechnology advancements have allowed many possibilities in modifying dental materials at a nano-scale, such as creating nanofibers for reinforced materials in dental composite restoration. Nanofibers can be produced through several methods including electrospinning. Electrospinning is highlighted as the most preferred technique for producing nanofiber due to its cost-effectiveness, efficiency, and ease of processing, resulting in the production of nanofibers with promising mechanical and functional properties in dentistry.

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