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REVIEW

PMMA denture base material enhancement: a review of fiber, filler, and nanofiller addition

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Abstract: This paper reviews acrylic denture base resin enhancement during the past few decades. Specific attention is given to the effect of fiber, filler, and nanofiller addition on poly(methyl methacrylate) (PMMA) properties. The review is based on scientific reviews, papers, and abstracts, as well as studies concerning the effect of additives, fibers, fillers, and reinforcement materials on PMMA, published between 1974 and 2016. Many studies have reported improvement of PMMA denture base material with the addition of fillers, fibers, nanofiller, and hybrid reinforcement. However, most of the studies were limited to in vitro investigations without bioactivity and clinical implications. Considering the findings of the review, there is no ideal denture base material, but the properties of PMMA could be improved with some modifications, especially with silanized nanoparticle addition and a hybrid reinforcement system.

Keywords: denture base, PMMA, reinforcement, nanoparticles, fibers, fillers

Introduction

Although dental implants are increasingly used in the treatment of edentulous patients, in many cases a conventional complete denture is still the treatment of choice for medical and financial reasons.[1] An ideal denture base material should have adequate mechanical and physical properties, besides biocompatibility and aesthetics.[2] Poly(methyl methacrylate) (PMMA) is frequently used to fabricate denture bases due to its various advantages, including low cost, biocompatibility, ease of processing, stability in the oral environment, and acceptable aesthetics. However, it is not considered an ideal material because of its inferior physical and mechanical properties.[3]

Several studies have been conducted with the goal of enhancing the properties of PMMA by using different curing methods and/or incorporating fillers in its composition.[2,3] Addition of fillers and fibers to PMMA is a commonly used method to improve both its physical and mechanical properties.[3] This paper reviews different types of fibers and fillers added to PMMA denture base resin and evaluates their effect on the physical and mechanical properties. The review includes data and source information available from scientific papers, reviews, and abstracts published from 1974 to 2016. The published material was searched in dental literature using general and specialist databases (Google scholar/PubMed database) and the keywords: denture base, PMMA, reinforcement, nanoparticles, fibers, and fillers.

Discussion

Many additives have been suggested to enhance the properties of denture base resin, such as fibers, fillers, or nanofillers (Table 1).

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Fibers

Reinforcement of acrylic resin with fibers has been reported to improve the flexural and impact strength as well as the fatigue resistance of the resin.[4] Several studies have been conducted using different types of fibers, such as nylon, polyethylene, polyamide fiber, and particularly glass fiber, due to their biocompatibility and superior aesthetics and mechanical properties.[4,5]

Glass fiber

Glass fiber reinforcement has been found to significantly increase the flexural strength, impact strength, toughness, and Vickers hardness of acrylic resin.[6–10] Also, a significant reduction in deformation of the denture base to less than 1% deformation was found.[6] Moreover, a recent study found that the position of glass fiber within the denture base affects its flexural properties. Improvement of flexural strength, toughness, and flexural modulus was obtained from placement of glass fiber close to the surface of the denture base on its tensile stress side. When glass fiber was placed in neutral stress area, only flexural toughness was improved, and when placed in the compressive side, surface flexural modulus was increased.[11] However, one study indicated that glass fiber impregnation into acrylic resin did not affect its linear dimensional stability.[12]

Preimpregnated and silane [3-(Trimethoxysilyl) propyl methacrylate (TMSPM)]-treated glass fiber also increased the flexural strength[13] and impact strength of acrylic resin.[14,15] Silanized glass fiber was found to be biocompatible when added to heat-cured and light-cured resins.[6,16] Moreover, fiber-reinforced nanopigmented PMMA showed reduced porosity and *Candida albicans* adherence.[6]

Polyamide fiber

Polyamide fiber includes both Nylon and Aramid (Kevlar, DuPont, Wilmington, DE, USA) fiber. Aramid fiber-reinforced denture base resin was found biocompatible, and additionally its flexural strength and flexural modulus were increased.[17] However, the hardness of the resin decreased with increasing fiber concentration. Also, its yellow color is considered a drawback.[18,19] Nylon increased the fracture resistance of PMMA, as it has high resistance to continual stress. Therefore, incorporating nylon fiber in PMMA increased its structural elasticity.[20]

Polyethylene and polypropylene fibers

Polyethylene fiber significantly increased the impact strength of PMMA, and a further increase was observed with fiber

Table 1 Summary of fiber, filler and nanofiller additive studies and its effect on denture base resin

Additives	Modifications	Effect		Comments
		Increase/improve	Decrease/weaken/ (no effect)	
Fiber	Glass fiber	Flexural strength, impact strength, toughness and hardness,[6–9] and reduced deformation of the denture base.[6]	No effect (linear dimensional stability).[12]	The most common reinforcement repair material under research is the silanated glass fiber. It highly improves the physical properties of denture base resin in addition to its biocompatibility. Also its ease of application renders its priority for use.
	Silanized glass fiber	Flexural strength[13] and impact strength.[14,15] Biocompatible[6,16] and reduced porosity and *C. albicans* adherence.[6]		
	Aramid	Biocompatible, flexural strengths, and flexural moduli.[17]	Hardness, yellow color.[18,19]	
	Nylon	Fracture resistance and structural elasticity.[20]		
	Polyethylene	Impact strength, elastic modulus, and toughness.[7,21]		
	Polypropylene	Impact strength.[15]		
	Silanated polypropylene	Transverse, tensile, and impact strengths.[22]	Wear resistance.[22]	
	OPEFB	Flexural strength and flexural modulus.[23]		
	Vegetable fiber	Flexural modulus.[24]	Flexural strength.[24]	

Alumina	Al_2O_3	Thermal conductivity,[25,29–31] flexural strength, impact strength, tensile strength, and surface hardness of the resin.[26,29,31,32]	Impact and tensile strength of PMMA.[30,34]	Alumina filler mainly used to improve thermal conductivity, and the silanized type improves physical and mechanical properties of denture base resin.
	Silane-treated Al_2O_3	Compressive, tensile, flexural strength, wear resistance,[25,35,36] water sorption, and solubility.[26]	No effect (surface roughness and water sorption).[30,34]	
	Al_2O_3 NPs	Thermal stability,[28] flexural strength, water sorption, solubility,[37] and biocompatibility.[38]		
Zirconia	Zo_2	Flexural strength.[26,40–42] Impact strength, fracture toughness, and hardness.[26,40,41] Water sorption and solubility.[26]	Flexural strength[43] impact strength, and surface hardness.[42] Water solubility and water sorption.[41,42]	Observable improvement in denture base properties with zirconia NPs incorporation. Silanized zirconia NPs resulted in superior mechanical properties and adequate surface properties of PMMA denture base resin.
	Zo_2 NPs	Impact strength, flexural strength and radio-opacity.[44,46] Compressive strength, fatigue strength, fracture toughness and hardness,[46,48,49] as well as color properties.[51]		
	Silanized zirconia NPs	Flexural strength, impact strength,[51–54] and hardness. Surface roughness slightly increased, and porosity decreased.[54,55] Tensile and fatigue strength and decreased water sorption and solubility.[55]		
	Zirconia nanotubes	Flexural strength.[56]		
Silver	Silver	Flexural and fatigue strength, thermal diffusivity.[31] Water sorption, water solubility.[73] Tensile and flexural strengths.[25]	No effect (impact and transverse strength, hardness, and surface roughness).[73]	Silver mainly used as antimicrobial agent, it was effective in reducing *Candida* adhesion.
	Silver NP	Antifungal properties,[67–69] thermal conductivity, and compressive strength.[74,75] Not cytotoxic.[38,68] Viscoelastic properties.[78]	Tensile strength.[76] Poor color stability.[71,77] No effect (*C. albicans* adherence).[72]	It also improved thermal conductivity, and it is biocompatible.
Titanium	TiO_2	Flexure strength, fracture toughness, and hardness.[26,40,57,58] Impact strength, water sorption, and solubility.[26]	Flexure strength.[40,57]	TiO_2 NPs addition improves the mechanical and surface properties of denture base resin as well as thermal conductivity. An extra improvement was noticed with titanate-coupling of agents.
	TiO_2 NPs	Thermal stability, E-Modulus.[28]	Flexural strength and toughness.[9]	
	Titanate-coupling agents	Transverse strength, hardness, water sorption and solubility.[61]	Surface roughness.[61]	
	$BaTiO_3$	Radio-pacifier,[64] thermally stable.[65]	Fracture toughness.[64] High density.[65]	
Nano-gold		Flexural strength and thermal conductivity.[79,80]		Noticed improvement but need further investigations.
HA	Silane-treated HA filler	Flexural strength and flexural modulus.[83,84]	Flexural properties on water storage.[83]	
	HA NPs	Fatigue and compression strengths.[48]		
Carbon Family	Nano-carbon	Impact strength and flexural strength.[97]	Hardness.[97]	Carbon NPs and nanotubes enhance denture base strength. Meanwhile silanized NPs improved the properties of denture base resin but it was decreased with sailanized nanotubes.
	SWCNT'S	Impact and transverse strength.[98]	Hardness.[98]	
	MWCNTs	Flexural strength and resilience.[100]	No effect (flexural strength).[99]	

(*Continued*)

Table 1 (*Continued*)

Additives	Modifications	Effect: Increase/improve	Effect: Decrease/weaken/no effect	Comments
	ND	Hardness and thermal conductivity,[101,102] impact strength, fracture toughness, and scratch resistance.[102,103]	Fatigue resistance.[100]	Although few researches have been done on ND, it showed improvement in physical and mechanical properties, as well as thermal conductivity of denture base resin.
Silica based	Glass flake	Fracture toughness.[40]		Different forms of silica were used. The silicanized and fluoridated one improved the mechanical properties and maintained surface properties of denture base resin, as well as improved denture hygiene.
	Mica	Thermal dimensional properties,[89] and hardness.[90]	Flexural strength.[90]	
	SiO_2	Impact, transverse strength, and hardness.[85]		
	Surface-treated silica	Flexural strength.[87]	No effect (hardness)[87]	
Hybrid reinforcement	Hybrid fibers	Flexural strength and toughness.[7]		Although few researches have been done on hybrid reinforcement, they revealed superior surface properties, mechanical properties, thermal conductivity, and biocompatibility.
	Metal oxides and ceramics	Flexural strength and toughness[116] surface roughness,[109] tensile modulus,[114] hardness,[115] and thermal conductivity,[116] reduced shrinkage,[107] and have antibacterial properties without showing cytotoxicity.[108]		
	Fiber and other fillers	Impact strength, hardness,[112] surface roughness, thermal conductivity,[113] compressive, and fatigue strengths.[108]		

Abbreviations: *C. albicans, Candida albicans*; HA, hydroxyapatite; MWCNT, multiple wall carbon nanotube; ND, nano-diamond; NP, nanoparticle; OPEFB, oil palm empty fruit bunch; PMMA, poly(methyl methacrylate); SWCNT, single-wall carbon nanotube.

surface treatment.[7,21] Woven polyethylene fiber reinforcement can significantly increase the elastic modulus and toughness of PMMA. However, the procedures of woven fiber etching, preparing, and positioning were found impractical.[21] Polypropylene fiber increased the impact strength of PMMA, and surface treatment of the fiber resulted in a further increase in its impact strength.[15] The highest impact strength was obtained with polypropylene fibers treated with plasma, which can be used to strengthen acrylic resin and reduce fracturing.[15] A recent study found that incorporating silanized polypropylene fiber in heat-cured PMMA resin significantly improved its transverse, tensile, and impact strengths, but its wear resistance was highly decreased.[22]

Natural fibers

Natural fibers were suggested to reinforce denture base resins, among which are, oil palm empty fruit bunch (OPEFB) and vegetable fiber (ramie fiber). OPEFB significantly increased the flexural strength and flexural modulus of acrylic resin.[23] Short ramie fiber also increased the flexural modulus of acrylic resin compared with conventional PMMA, but its flexural strength decreased as a result of weak interfacial bonding. The drawback of this fiber was its presentation in a long form, which requires extra work, ie, cutting and preparation.[24]

Fillers

Several studies were conducted on using fillers (Table 2) to strengthen denture base resin, and they found significant improvement in its properties. Reinforcement of PMMA with metal oxides improved the physical and mechanical properties of the material, as well as patients' sensation of hot and cold stimuli. Consequently, better food sensation and healthier oral mucosa were expected by adding metal fillers to denture base resin.[25–27] Recently, the incorporation of nanofillers (Table 2) has been suggested to improve PMMA properties. The high surface area, fine size, and homogenous distribution of nanofillers improved the thermal properties of PMMA and increased its thermal stability compared with pure PMMA.[26–28] The properties of resin reinforced by nanofillers depend on the size, shape, type, and concentration of the added particles.[28]

Metal oxides

Alumina (Al_2O_3)

Arora et al[29] recently reviewed the effect of alumina addition and reported a positive impact on the properties of acrylic resin. Addition of alumina powder to acrylic resin

Table 2 Classification of reviewed fillers and nanofillers

Additives	Filler (Size -μm)	Nano-filler (Size -nm)
Metal oxides	Aluminum oxide (Al_2O_3)	Al_2O_3
	Zirconium oxide (ZrO_2)	ZrO_2 and nanotube
	Titanium oxide (TiO_2)	TiO_2
Noble metals	Silver (Ag)	AgNPs
		Gold (Au)
		Platinum (Pt)
		Palladium (Pd)
Mineral	HA	HA
	Silicon dioxide (SiO_2)	SiO_2
	Mica	
		Nanoclay
		HNT
Carbon family		Nano-carbon
		NDs

Abbreviations: HA, hydroxyapatite; HNT, Halloysite nanotube; ND, nanodiamond; NP, nanoparticle.

improved its thermal conductivity and, accordingly, patient satisfaction was expected to increase.[25,30–33] In addition, reinforcing PMMA with aluminum increased the flexural strength, impact strength, tensile strength, compressive strength, and surface hardness of the resin.[26,30,32,34] Warpage also decreased significantly after addition of aluminum to PMMA. On the other hand, some studies found that adding aluminum decreases both the impact and tensile strength of PMMA.[31,35] The resin was weakened due to stress concentration around the embedded metal and its poor adhesion to the polymer.

However, several methods such as sandblasting, silanization, and metal adhesive resins were suggested to improve the bond between the acrylic resin and metal surface.[27] Treating aluminum oxide particles with a coupling agent increased the flexural properties of acrylic resin.[36,37] Also, silane-treated aluminum particles significantly increased the compressive, tensile, and flexural strength and the wear resistance of reinforced denture base resin.[25,37]

Surface roughness and water sorption were not significantly changed with aluminum-reinforced denture resin.[31,35] However, one study found a significant decrease in water sorption and solubility after addition of Al_2O_3,[26] and an increase in water sorption was found by another study.[31]

Safi[28] concluded that adding Al_2O_3 nanoparticles (NPs) to PMMA increases its thermal stability compared with pure PMMA. Addition of silanized Al_2O_3 NPs to acrylic resin improved the thermal properties (decreased the thermal expansion coefficient and contraction) and flexural strength of acrylic resin, and at the same time this addition decreased water sorption and solubility.[38] A recent study reported that alumina NPs have a good level of biocompatibility when added to microwave-treated and untreated PMMA powder.[39] The disadvantage of aluminum-reinforced PMMA is discoloration of the resin, which limits its use to areas where it is not visible.[38] Although the addition of Al_2O_3 to PMMA significantly increased thermal conductivity, the flexural strength values of PMMA were not significantly changed.[33]

Zirconia (ZrO_2)

Several studies found that incorporating zirconia (ZrO_2) fillers in PMMA significantly increased its flexural strength.[26–42] However, a slight decrease in flexural strength was also reported; it may result from clustering of the particles within the resin, which weakened the material.[43] In addition, the impact strength, fracture toughness, and hardness of PMMA were increased significantly by incorporating ZrO_2.[26,40] On the other hand, one study found an insignificant increase in the impact strength and surface hardness of zirconia-reinforced resin compared with unreinforced PMMA.[41] A decrease in both impact strength and surface hardness was also reported.[42] Also, addition of ZrO_2 significantly increased the thermal conductivity of PMMA.[33] Different results were obtained regarding the effect of ZrO_2 on the water sorption and solubility of PMMA. It was found that adding ZrO_2 significantly decreased the water sorption and solubility of PMMA,[26] while an insignificant difference in water solubility and an increase in water sorption within the limit of ADA specifications were also reported.[41,42]

Adding zirconia NPs was suggested to improve the mechanical properties of PMMA.[44,45] Incorporating zirconia NPs in PMMA increased its impact strength, flexural strength,[44,46,47] compressive strength, fatigue strength, as well as its fracture toughness and hardness.[46,48,49] In addition, it may have an antifungal effect and may play a preventive role in patients susceptible to fungal infections.[50] On the other hand, one study found an insignificant increase in the hardness of nano-ZrO_2/PMMA, and its surface roughness was not significantly changed[44] Safi et al,[51] studied the effect of zirconia NP addition on the color properties of PMMA and did not find any noticeable color changes.

Poor wettability between fillers and the resin matrix reduced improvement of the physical and mechanical properties of PMMA. Therefore, a silane coupling agent was used to improve the bond strength between zirconia NPs and PMMA. It resulted in increased flexural strength and impact strength of acrylic resin, but its tensile strength was not improved.[51–54] However, one study found that silanized zirconia NPs improved the tensile strength and fatigue strength of PMMA.[55] Also hardness increased significantly and surface roughness increased slightly when silanized zirconia NPs were incorporated in acrylic resin, while apparent porosity,[54,55] water sorption, and solubility decreased.[55]

In addition, zirconia nanotubes showed a better reinforcing effect than zirconia NPs. In contrast to zirconia NPs, surface treatment would lower the reinforcing effect of zirconia nanotubes. It was found that flexural strength was maximized when 2wt% untreated zirconia nanotubes were added to PMMA.[56]

Titanium (TiO_2)

Several studies have investigated the effect of adding titanium dioxide (TiO_2) on the properties of PMMA. It was found that adding TiO_2 particles could improve the flexure strength, fracture toughness, hardness of PMMA,[26,40,57,58] as well as thermal conductivity.[33] In addition, a significant increase in impact strength[59] and a significant decrease in water sorption and solubility were found upon addition of TiO_2 to PMMA.[26] Conversely, some studies found that TiO_2 did not improve the flexure strength of PMMA, which could be attributed to clustering of the particles within the resin, causing its weakness.[40,57]

Safi[28] found that modifying PMMA with TiO_2 NPs has an effect on its thermal (decrease in the thermal expansion coefficient and contraction) and mechanical (decreased E-Modulus) stability, while a reduction in flexural strength and toughness was reported.[9,59] Adhesion between the resin matrix and filler particles is very important in order to enhance the composite's properties. Accordingly, a titanium coupling agent could be useful for improving the properties of titanium-reinforced PMMA.[60] Incorporation of silanized TiO_2 NPs in PMMA improved the impact strength, transverse strength, and surface hardness of the resin and decreased its water sorption and solubility. Moreover, surface roughness increased with the addition of 3wt% of silanized TiO_2 NPs to acrylic resin.[61] Addition of apatite-coated titanium dioxide and fluoridated apatite-coated titanium dioxide after treatment with ultraviolet A irradiation of PMMA inhibited *Candida* adhesion due to their antifungal effect, and their use could be beneficial in obtaining appropriate denture hygiene.[62,63] Addition of barium titanate ($BaTiO_3$) as a radiopacifier to PMMA showed a slight decrease in fracture toughness properties.[64] It was found that PMMA/$BaTiO_3$ composite is thermally stable, but its increased density affects denture retention. [59,65]

Noble metals

Silver (Ag)

Several studies found that addition of silver NPs (AgNPs) to denture base acrylic resin displayed antifungal properties,[66–69] especially at high concentrations,[70] and acted like a latent antifungal material with low-releasing Ag^+.[71] On the contrary, Wady et al[72] found that incorporating silver NPs in PMMA did not affect the adhesion of *C. albicans* and biofilm accumulation.

Silver has an antimicrobial effect; its addition to PMMA could reduce microbial adhesion and colonization.[66,67] Therefore, its use could be beneficial for immune-compromised and geriatric patients.[67] In addition, silver-reinforced PMMA resin has increased flexural and fatigue strength and improved thermal conductivity.[32,33] However, it was found that incorporating 0.5% of antimicrobial silver–zinc zeolite in heat-cured acrylic resin did not affect its impact and transverse strength, the surface hardness, and the surface roughness of the resin. It did not change its color, but a significant decrease in water sorption and an increase in water solubility were found in the acrylic resin.[73] On the other hand, it was suggested that, depending on its percentage, adding silver may negatively affect the mechanical properties of denture base resin.[66] Incorporating silane-treated silver particles significantly increased the compressive strength of PMMA. Also, addition of 10wt% and 20wt% silane-treated silver fillers enhanced the tensile and flexural strength of PMMA.[25] Addition of silver powder to PMMA significantly increased thermal conductivity; the flexural strength values of PMMA were not significantly changed.[33]

The physical and mechanical properties of PMMA were enhanced by the addition of silver NPs, including improvement of thermal conductivity and compressive strength.[74,75] Therefore, it is recommended to be used in the palatal area of maxillary acrylic resin dentures.[74] Also, it was found that PMMA-silver NPs are not cytotoxic.[39,68] However, tensile strength did not change significantly after incorporating 0.2% of AgNPs in comparison with unmodified PMMA, but it decreased significantly after incorporation of 2%.[76] In addition, poor color stability of PMMA-AgNPs was reported.[71,77] Incorporating AgNPs in acrylic denture base material can improve its viscoelastic properties.[78]

Nano-gold (Au), platinum (Pt), palladium (Pd)

Nano-gold (Au) and platinum (Pt) NPs recently were suggested to improve the properties of PMMA denture base. The studies available on the effect of adding nano-gold to PMMA are still limited at the present time. It has been observed that incorporating gold NPs considerably improved the flexural strength and thermal conductivity to almost double the value of pure PMMA, which could lead to more patient satisfaction.[79,80] Addition of Pt NPs could improve mechanical properties of PMMA and provide antimicrobial effect.[81] It was found that platinum significantly increased the bending deflection of PMMA and that palladium improved the bending strength when compared to silver and gold, which showed the lowest value of bending strength. Addition of gold and palladium improved Vickers hardness of PMMA and was decreased with the addition of platinum.[82]

Minerals

Hydroxyapatite fillers

Hydroxyapatite fillers (HA) added to PMMA resulted in superior mechanical properties. It increased the flexural strength as well as the flexural modulus of PMMA.[83] The interfacial interaction between HA filler and the PMMA matrix is enhanced by treatment with γ-MPS.[83,84] But a reduction in the flexural properties on water immersion was attributed to water's plasticizing effect, which weakens the bonding between the HA filler and the PMMA matrix.[83] The addition of HA NPs also increased both the fatigue and compression strength of PMMA resin in comparison with pure PMMA,[48] in addition to significant increase in thermal conductivity.[33]

Silicon dioxide (SiO_2)

The mechanical and thermal properties of PMMA were enhanced by the incorporation of silicon dioxide (SiO_2) NPs.[28] Improvement of both the impact and transverse strength of PMMA was achieved by the addition of SiO_2 NPs. Surface hardness also increased with a higher SiO_2 NP concentration.[85] However, improved hardness and fracture toughness were found with a low concentration of SiO_2 NPs. Increasing its content resulted in agglomeration and crack propagation, which reduces both hardness and fracture toughness.[86] Addition of surface-treated silica improved the flexural strength of PMMA but did not affect hardness.[87] On the other hand, a recent study found that silica NPs adversely affect the flexural strength of PMMA.[88]

Silica-based filler

Reinforcement of acrylic resin with glass flakes enhanced its fracture toughness, and the use of silane coupling resulted in further improvement of the resin's properties.[40] Micas are a group of lamellar silicate minerals, which have been suggested to improve resin's properties. These lamellar silicate minerals are characterized by their high aspect ratio, and they improved the mechanical, thermal, as well as dimensional properties of PMMA.[89] The hardness of acrylic resin increased with the incorporation of mica, but its flexural strength was reduced because of mica's weak bond with the acrylic resin.[90] It was also found that addition of fluoride glass fillers to PMMA decreased microbial adhesion, although it slightly increased surface roughness of the denture base resin.[91–93] Nanoclay is another material which is used to improve the properties of composite and acrylic polymers. The addition of Nanoclay particles to PMMA improved its thermal conductivity, while it had a negative effect on the flexural strength.[94] Placing silicon carbide filler powders in the palatal region of dentures can improve the thermal conductivity of PMMA without reducing strength or increasing weight.[33] The halloysite nanotube is a silica-based naturally occurring mineral which introduced by Abdallah[95] in 2016 to improve the properties of PMMA. Halloysite nanotube increased hardness of PMMA when added in small percentages, while the flexural strength and Young's modulus did not show a significant increase.

Carbon family fillers

Carbon fillers are not commonly used to reinforce PMMA because of biological problems, poor aesthetics, as well as difficulty in handling and polishing.[18] But nowadays, nano-carbon is one of the main branches of nanotechnology.[96]

Nano-carbon

Addition of 1% of carbon nanotubes to PMMA was found to significantly increase the impact strength and flexural strength of the resin, but its hardness was decreased.[97] It was also found that adding 1.5% of single-walled carbon nanotubes significantly increased the impact and transverse strength of PMMA, but significantly decreased its surface hardness.[98] Conversely, one study reported an insignificant effect of adding single-walled carbon nanotubes on the flexural strength of PMMA.[99] Addition of 0.5% and 1% of multiple-wall carbon nanotubes (MWCNTs) improved the flexural strength and resilience of PMMA, while its fatigue resistance was decreased with higher concentrations of multiple-wall carbon nanotubes.[100]

Nano-diamonds

The outstanding properties of nano-diamonds (NDs), ie, high hardness and thermal conductivity, suggested its use to improve the mechanical properties of PMMA.[101,102] NDs significantly increased the impact strength of PMMA, and also improvement in fracture toughness was found, but only at the lowest concentration of NDs.[103] Moreover, heat-treated NDs increased the scratch resistance of PMMA.[104] Some drawbacks were attributed mainly to agglomeration of the NPs, which could act as points of stress concentration.[105]

Hybrid reinforcement

Reinforcement of PMMA by more than one type of fiber was first suggested by Vallittu in 1997.[106] As listed in Table 3, the combination may be between different fibers,[7] different metal oxides and ceramics,[107–111] and fibers with metal oxides,[112,113] or ceramic materials.[48,114–116]

Hybrid fiber reinforcement significantly increased the flexural strength and toughness of reinforced acrylic resin.[14] Similar results were also obtained by incorporating metal oxides and ceramics, especially NPs, in PMMA.[116] In addition to improving surface roughness,[109] tensile strength, flexural modulus,[114] hardness, and thermal conductivity,[116] and radiopacity[111] as well as reducing shrinkage,[107,110] it has antibacterial properties without showing cytotoxicity.[108]

A combination of fibers and other fillers also increased impact strength, hardness,[112] surface roughness, and thermal conductivity,[113] as well as compressive and fatigue strengths.[71]

Summary and clinical implications

For years, acrylic dental prosthesis has been used for treatment of edentulous patients to improve their quality of life. It has several advantages including, considerable price, aesthetics, and ease of manipulation. However, it is susceptible to fracture or deformation due to its inferior mechanical and physical properties. Several attempts have been implemented to improve the properties of PMMA including addition of reinforcing material as fibers, fillers hybrid reinforcement, and, recently, NPs. However, the most effective reinforcement is not apparent, and clinicians are confused about designing such reinforcement. Moreover, some authors reported that reinforcement involved the addition of a foreign material to prostheses, and may thus be a risk factor for fracture development, rather than fracture prevention. Currently, reinforcement has two important purposes on a prosthesis. The initial purpose is to improve the strength and prevent fracture, and of the previous studies were conducted with a focus on this purpose. The second purpose is to improve the stiffness and prevent residual ridge resorption and overloading to residual teeth or structures. To summarize this review, reinforcements within denture base acrylic resins undoubtedly had some efficacy in improving the physical and mechanical properties, but the levels varied by material, form, concentrations, surface treatment, and position of the reinforcement. Considering these results, clinicians had better placed some kind of reinforcement in all removable dental prostheses to prevent prosthetic and other complications. However, most of the previous studies were carried out in terms of improving the strength, rather than the rigidity, and studies aimed at improving rigidity remained insufficient even in experimental model and specimen studies. Furthermore, clinical studies about the effect of reinforcement on both prostheses and patients were very few, and in particular, there were no randomized long-term clinical studies comparing prostheses with and without reinforcement. Therefore, further studies focusing on the rigidity of prostheses with reinforcement and its effect on underlying structures such as the residual ridge or implant as well as longitudinal clinical studies, are necessary to ensure the effect of reinforcement within dental prostheses. In the future, the possibilities to use a high strength biomaterial with low modulus should also be taken into consideration.

Table 3 Different hybrid reinforcement materials

Hybrid type	Hybrid materials
Fibers	Glass fiber + polyethylene fibers[7]
Fillers	– Al_2O_3 + ZrO_2[114,109] – ABWs + Al_2O_3[115,108] – ZrO_2-TiO_2[116]
Fibers + fillers	– Polyester fiber reinforced PMMA + (clay, glass powder, SiO_2, or ZrO_2)[112] – Al_2O_3 + plasma-treated polypropylene fiber[113] nHA particles, micro-zirconia, glass fiber, and Kevlar fiber (PMMA-nHA and glass fiber), (PMMA-ZrO_2 and glass fiber) (PMMA-nHA and Kevlar fiber), (PMMA-ZrO_2 and Kevlar fiber)[48]

Abbreviations: ABW, aluminum borate whisker; nHA, nano-hydroxyapatite; PMMA, poly(methyl methacrylate).

Conclusion

Based on this comprehensive review it can be concluded that:

- Glass fiber reinforcement significantly increases the mechanical properties of PMMA. Natural fibers (OPEFB) and vegetable fiber can be used, but further investigations are needed.
- Obvious enhancement in the properties of denture base resin material properties was found with the addition of

NPs and nanotubes, depending on the application and manipulation.

- Silane coupling agents play a central role in improving bonding between fillers and the resin matrix, and they subsequently improved the resin's properties.
- The newest reinforcement system is a hybrid one. Hybrid fiber, hybrid fillers, or hybrid fiber and filler may considerably enhance the properties of PMMA.
- Multiple studies were conducted in vitro, so further studies in vivo are needed, as well as clinical studies.

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