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Review

Biodegradation of acrylic based resins: A review

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ABSTRACT

Objectives. The development of different types of materials with application in dentistry is an area of intense growth and research, due to its importance in oral health. Among the different materials there are the acrylic based resins that have been extensively used either in restorations or in dentures. The objective of this manuscript was to review the acrylic based resins biodegradation phenomena. Specific attention was given to the causes and consequences of materials degradation under the oral environment.

Data and sources. Information from scientific full papers, reviews or abstracts published from 1963 to date were included in the review. Published material was searched in dental literature using general and specialist databases, like the PubMED database.

Study selection. Published studies regarding the description of biodegradation mechanisms, *in vitro* and *in vivo* release experiments and cell based studies conducted on acrylic based resins or their components were evaluated. Studies related to the effect of biodegradation on the physical and mechanical properties of the materials were also analyzed.

Conclusions. Different factors such as saliva characteristics, chewing or thermal and chemical dietary changes may be responsible for the biodegradation of acrylic based resins. Release of potential toxic compounds from the material and change on their physical and mechanical properties are the major consequences of biodegradation. Increasing concern arises from potential toxic effects of biodegradation products under clinical application thus justifying an intensive research in this area.

Contents

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1. Introduction

Acrylic based resins consist of polymeric materials based on polymethylmethacrylate. These dental materials are the result of a free radical polymerization reaction. They can be classified as chemical, heat or light activated depending on the factor that initiates the reaction. Chemical or autopolymerized materials involve a chemical activator like N,N-dimethyl p-toluidine [1]. For heat-polymerizing materials, heat can be generated by hot water bath or microwave energy, while the light polymerizing uses visible light as energy source [2–4].

Acrylic based resins are frequently used in daily dental practice, as they are able to provide the essential properties and necessary characteristics to be used in diverse functions. Most common use of the materials includes denture bases and denture liners, orthodontic appliances and temporary crowns [4–6].

Denture bases are composed of pre-polymerized polymethylmethacrylate (PMMA) or polyethylmethacrylate (PEMA) powder particles along with a peroxide initiator and a pigment, which are mixed with methacrylate monomers (methylmethacrylate, hexamethyleneglycoldimethacrylate, hydroxylethylmethacrylate, *n*-butylmethacrylate, tetrahydrofurfurylmethacrylate) and cross-linking agents such as ethyleneglycoldimethacrylate, trimethylolpropane trimethacrylate or 1,6-hexanediol dimethacrylate [1,7–9].

Denture liners are used to improve the fit of denture bases, thus re-establishing the retention, support and stability of removable prostheses [10]. Several types of these materials are available, they can be hard reline resins or soft lining materials. Soft lining materials can be divided into two groups [4]. The first comprises materials in which the liquid is made of monomer components, such as methyl, ethyl or butylmethacrylate and phthalates, citrates or sebacates as plasticizers. The second group is similar to tissue conditioners, in which the liquid contains a mixture of plasticizers and ethyl alcohol [4,11–14].

Orthodontic appliances are used for space maintenance, thumb deterrent, tipping teeth, overbite reduction, block movements and retention. PMMA is the material most commonly used for manufacturing the polymeric part of these orthodontic appliances [15].

Temporary crowns are used during the interval between tooth preparation and placement of the definitive crown. There are several types of acrylic resin materials available for provisional restorations as PMMA or PEMA resins [16].

An important issue regarding the clinical application of the acrylic based resins is their biodegradation. It can be defined as the changes on their chemical, physical and mechanical properties due to the oral environment conditions.

In the oral cavity the materials are exposed to a rather complex milieu that comprises different endogenous (proteins, enzymes, polysaccharides, bacteria) and exogenous substances (all different sorts of compounds coming from the diary intake diet). These components establish a complex and intricate interplay of interactions, which result along with an important mechanical action, in a general biodegradation phenomena towards the biomaterials present in the oral cavity. These processes may permanently alter the properties of the material and compromise its function.

In addition, biodegradation of a biomaterial can produce leachable products, which in turn may induce a series of biological responses on cells and tissues. Biodegradation impact on the biocompatibility of acrylic materials is controversial [17] but concern about its clinical significance is a fact as subjective and objective complaints about these materials are increasing [18].

2. Causes for biodegradation

The polymeric materials were classically recognized as large stable structures with a high degree of resistance to biodegradation. However, several studies conducted especially with composites materials, showed that polymers may be subject to a myriad of degradation processes in the oral cavity [19,20].

Polymer degradation does not occur as a result of isolated processes, multiple factors as saliva, chewing, thermal and chemical dietary changes may be responsible for the biodegradation processes [20].

2.1. *Saliva components*

Water is the most abundant component of saliva as such is one of the main factors to cause biodegradation. The oral environment necessarily facilitates water sorption from the saliva to the resin, which is a polar material. Water molecules can easily penetrate the polymer network allowing the diffusion of unbound/uncured monomers and/or additives from the material network [4,15,21].

There are two conditions that influence the amount of water diffusion to denture resins. One is the water diffusion

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coefficient of the material that affects the time needed for its saturation with water. The other one is the amount of residual components that are release for the medium and replaced by water molecules [19–21].

Water sorption has been shown by several authors to follow Fickian diffusion kinetics [22–24]. Therefore, one might expect a typical polymeric dental material to become saturated with its aqueous environment within 1–2 months after placement.

Polymeric structures and dental materials in particular may also be chemically degraded in aqueous solutions essentially through two mechanisms: hydrolysis and enzymatic reaction [19,20]. Salivary enzymes can degrade polymers through attacks on the side chains, producing both potentially harmful by-products as well as a deterioration of the properties of the network. The composition of the monomers producing the network is a major factor in determining the extent of degradation, especially when enzymes are responsible. Various esterases that have been shown to be present in saliva can promote esterification of methacrylates. The effect of enzyme degradation on mechanical properties has been manifested as a reduction in surface hardness and wear resistance [19,20,25–31].

Interactions between oral microbes and the polymer dental materials may also occur, although little information is available regarding this possibility. An *in vitro* study conducted by Willershausen et al. [32] has shown that bacteria can colonize the surfaces of resin-based dental materials. They have also found an increase in the roughness, suggesting some surface degradation effect caused by bacteria colonization.

2.2. Chewing force

Biodegradation of the materials in the oral cavity can also be induced by fatigue, which is caused by relatively weak repetitive loads such as ordinary chewing force. A continuous application of mechanical and environmental loads leads to progressive degradation and crack initiation and growth, resulting in catastrophic failure of the resins. This process is further assisted by pre-existing voids introduced during the material processing and residual stresses [33]. Chewing can also apply shear and compression forces on denture teeth causing wear [34].

The mechanical loading developed on the material is usually study by means of cyclic loading. A chewing simulator designed to imitate the chewing forces that are produced during function is used. It has been realized that static evaluation of a material may not be as important as cyclic fatigue values for materials utilized in the oral cavity. The simulator usually acts in a frequency of 2 Hz with sinusoidal loads cycling for 11,000 and 100,000 cycles at a load level of 60% of the fracture load of non-cycled specimens [33].

The effect of chewing on the release of substances from acrylic based resins is controversial. Simulation of mastication by dynamic cycling did not produce any significant increase in the leaching of phthalate esters in soft polymers except those with ethanol [35]. Nevertheless Graham et al. [36] has shown that clinically tested denture lining materials appeared to lose significantly more plasticizer than materials stored statically *in vitro* over the same time frame.

2.3. Thermal and chemical dietary changes

Intraoral temperature changes may be induced by routine eating and drinking. These temperature changes produce a hostile environment for the materials as they have a different coefficient of thermal expansion compared to natural tooth. Thermal fluctuations encountered *in vivo* can induce surface stresses due to the high thermal gradients near the surface. Mechanical stresses induced by different thermal changes can directly induce crack propagation through bonded interfaces influencing the bond strength between denture base and reline materials [37,38].

The thermal changes are simulated in research through thermocycling. The specimens are immersed in almost extreme temperatures baths: 5 ± 2 and $55 \pm 2\,^{\circ}C$ with a dwell time that varies between 30 s and 1 min each [39].

Foods and drinks can also affect dental materials by the direct effect of their additives, like ethanol, and their capacity of changing the intraoral pH values [40].

3. Consequences of biodegradation

A major clinically significant consequence of acrylic based resins biodegradation is the release of potential toxic unbound/uncured monomers or/and additives from the polymer network. The released compounds may have a toxic effect on the oral cavity. With respect to materials stability, biodegradation may induce significant changes in materials physical and mechanical properties that may ultimately lead to the catastrophic failure of the material.

3.1. Release of compounds from acrylic based resins

The release of compounds from different types of acrylic based resins has been widely investigated [41]. The majority of studies refer to denture [7,18,42–49] and relining [4,12,36,47,50–53] materials of different chemical composition. Some few studies analyze orthodontic appliances [54], restorative materials [21,55] and tissue conditioners [52,56]. Generally the experimental conditions consists in incubating polymer specimens of different shapes (disks, rectangular, cylinders) and sizes prepared according to manufactures instructions in a liquid, at room temperature or $37\,^{\circ}C$, for periods of time ranging from hours to 1 or 2 months. Zissis et al. [47] conducted a longer study (38 months) on the release of residual monomer from denture base resins.

In most studies water is used as the leaching media [3,4,7,18,36,45,47–49,52,54,55,57–59]. Ethanol [21] and mixtures of ethanol/water [18,52,59] has also been used in order to increase the solubility of water insoluble compounds like phthalates [12].

The diffusion of residual monomers and other leachables components from acrylic based materials into human and artificial saliva has been investigated in some studies [6,12,18,41,42,44,52,53,60]. Kedjarune et al. [44] used unstimulated whole human saliva to evaluate the release of MMA from heat-cured and autopolymerized resins. Munksgaard [12] concluded that artificial saliva composed of an aqueous buffer with an esterase enzyme increased the rate of diffusion of phthalates from a soft lining acrylic material.

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Very few investigators have concentrated on evaluating the release of compounds from acrylic based materials in clinical studies. Baker et al. [60] have evaluated the concentration of residual monomer leached from autopolymerized resins in a clinical study. Residual monomer in saliva was detected for up to 1 week wearing either an autopolymerized acrylic appliance or a heat polymerized appliance but they only measured the percentage of one monomer: methylmethacrylate (MMA). Graham et al. [36] evaluated the release of phthalates from two soft denture lining materials based on PEMA polymers by an *in vivo* and *in vitro* study. The results have shown that a higher loss of plasticizer occurred *in vivo*, compared with the *in vitro* study. Phthalates were identified in saliva samples collected from patients wearing dentures [61] and orthodontic appliances [62]. Tsuchiya et al. [43] found significant amounts of formaldehyde and MMA in human saliva under *in vivo* conditions leaching from acrylic autopolymerized resins.

Recently, Gonçalves et al. [41] evaluated the *in situ* levels of residual MMA monomer of an autopolymerized acrylic resin in forty volunteers. High concentrations of residual monomer during the first 24 h of use were observed.

In spite of the different experimental methodologies the majority of published studies refers the elution of unbound components mainly MMA monomer [3,4,21,42,44,45,48,49,52–55,58], phthalate esters [21,36,50,56] and additives like benzoyl peroxide [18] as one of the main consequences of material biodegradation.

Unbound monomers and additives are eluted within the first hours after initial polymerization and its release is time-dependent [59]. Generally samples release the highest amount of residual monomers during the first 24 h after being processed [44,48] followed by a slow and moderate release over a long period of time [7]. In a long-term study, Sadamori et al. [63] reported that MMA decrease could be expressed in a hyperbola. Residual monomer was detected in dentures used up to 17 years, although the majority of this release occurred in the first 5 years.

Only a small number of studies have been devoted to investigate issues regarding the chemical processes involved in the release of compounds from acrylic based resins. The influence of pH on the biodegradation is reported in some studies [64]. Koda et al. [42] evaluated the influence of salivary acidity on the leaching properties of denture base acrylic resins and found that lower pH showed higher concentrations of MMA monomer.

Tsuchiya et al. [43,57] found significant amounts of formaldehyde, a compound formed as an oxidation product of the residual MMA monomer [65], leaching from autopolymerized denture base acrylic resins.

Methacrylic acid resulting from the hydrolysis of MMA was detected leaching out from acrylic denture base materials [42,59] and from soft lining materials [52] in water, artificial saliva and mixtures of ethanol–water. Benzoic acid derived from the benzoyl peroxide initiator has also been observed [42].

3.1.1. *Biological effects of release*

Products of acrylic based resins biodegradation have been suspected of being a contributing factor for chemical irritation [52], sensibilization and pain of the oral mucosa [43,46,59,66], ulceration [67], labial edema [68] and oral diseases such as burning mouth syndrome and denture stomatitis [56,67].

Phthalates and other esters of aromatic carboxylic acids used as plasticizers in reline acrylic materials may possess undesirable biological effects, particularly as xenoestrogens [6,12,56,59].

Reported allergic reactions associated with acrylic based resins [69–73] have been attributed to MMA monomer and additives as benzoyl peroxide [18].

Cell culture techniques have provided strong evidence that released compounds from acrylic based resins may induce a series of biological responses on cells.

It is beyond the scope of this work to review all the numerous publications that evaluate the effect of acrylic based resins on cells. Some very good reviews related to the subject have already been published [65,74,75].

Most studies have focused on the cytotoxicity of leached MMA monomer and its derivatives [44,51,75–89]. Both permanent (L 929 fibroblast and osteoblast) and primary cells as gingival fibroblast, dental pulp, periodontal ligament and epithelial cells are used in the studies [51,81,84–86]. Test systems vary considerably in the way cytotoxicity is measured but all indicate changes in basic cell structures, such as cell membrane integrity and cell functions like enzyme activities or the synthesis of macromolecules [81].

The mechanism of adverse effect caused by MMA monomer is thought to involve direct toxicity from released or residual MMA and oxidative stress created by free radicals that are released during the resin polymerization [78,81,87,89–91]. In recent years, investigators have been using gene expression analysis for the evaluation of MMA effect on the expression of antioxidant enzymes like glutathione [88,93]. Cell culture techniques have also provided strong evidence that residual MMA monomer in acrylic based resin biomaterials may cause genotoxicity [83,84,94,95] and change in cytokine/growth factor expression of cells [96]. Some studies have addressed the effect of other methacrylate monomers like isobuthylmethacrylate and 1,6-hexanedioldimethacrylate [51,96] major components in several relining acrylic materials. Cytotoxic effects on primary gingival fibroblasts and periodontal cells in dose-dependent manners were observed for those monomers [51].

The toxicity of methacrylate monomers differs according to their structure [97]. The structure–toxicity relationship of eighteen acrylic and methacrylic compounds was examined by Lawrence et al. [98] and Bass et al. [99]. They have concluded that acute toxicity correlated with water solubility. Dillingham et al. [100] reported that hemolytic activity of acrylates and methacrylates esters was related to lipophilicity (inversely related to water solubility) and that the mechanism of the action of the esters was membrane mediated and relatively nonspecific. Moreover Yoshii [96] evaluated the cytotoxicity of thirty-nine acrylates and methacrylates. All the acrylates evaluated were more toxic than the corresponding methacrylates. In both the acrylates and methacrylates, a hydroxyl group seemed to enhance the cytotoxicity of the materials.

Some authors have claimed that MMA monomers, by reacting with molecular oxygen may produce formaldehyde [43,57]. Formaldehyde has proved to be cytotoxic at much lower concentrations than MMA [43]. This compound is suspected to

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cause hypersensitivity reactions and to be a strong irritant to the mucous membranes even at concentrations as low as 0.63–1.25 mg/m^3 [65].

Phthalate esters used as plastificizers that can be released from acrylic based materials have been under evaluation for their cytotoxicity and estrogenic activity being considered as toxic compounds [52,56,91,101]. Moreover some polymerization initiators can also cause toxic problems. For example benzoyl peroxide was found to induce necrosis in human gingival cells [102].

A specific study was realized to examine the effects of pH changes on the cytotoxicity of eluates from denture base resins on oral epithelial cells. Results showed that cytotoxic components leaching were affected by pH [64].

3.2. *Changes on the physical and mechanical properties*

Acrylic based resins are subjected to a complex number of conditions intraorally that can alter its dimension and/or structural integrity. Biodegradation may affect not only the inner properties of the material but also the bond strength between denture bases and reline acrylic resins.

3.2.1. *Inner properties of acrylic based resins*

Most published studies have concentrated on the implications of water sorption leading to dimensional changes of the materials [103–105]. Its influence on physical and mechanical properties of acrylic polymers such as hardness [103,106], flexural strength [107–111], resistance to plastic deformation [108] and fatigue limit [112] has also been studied.

The water molecules can penetrate into the spaces between the polymer chains and push them farther apart. Consequently the secondary chemical bonding forces (van der Waals forces) between the polymer chains decline and results in weight and volume increase to cause an expansion. The greater absorption of water by the material, the greater will be the associated dimensional change [113].

With time water molecules can act as plasticizers, altering the mechanical properties of the polymer [114]. It seems obvious that if water has a plasticizing effect on the resins their mechanical properties after water immersion should decrease [106]. The research shows these results in some kind of resins but not in all. The difference in the chemistry of the resins may account for the different effect water immersion has on their mechanical properties. Regarding to strength, if the constituent that leaches out exerts a lesser plasticizing effect than the water molecules, then the strength of the denture polymer should decrease. Conversely, if the constituent that leaches out exerts a more profound plasticizing effect than water molecules, then the strength of the denture polymer should increase [109].

Considering the soft lining materials the plasticizer particles gradually leach out in aqueous environments. As they are responsible of impart flexibility to the soft liners, their release turns the material progressively more rigid and therefore lead to clinical failure [115]. The loss of plasticizer may cause decreased percent elongation and increase hardness values [116,117].

The amount of dimensional changes due to water sorption can be influenced by the type of resin, their thickness and the amount of cross-linked polymers. For example, a heat polymerized denture acrylic polymer takes a longer time than an autopolymerized polymer for water sorption to reach saturation because of its lower diffusion coefficient of water [109]. Nevertheless when studying water sorption, Arima et al. [118] found no significant differences between highly cross-linked autopolymerizing reline resins and heat-polymerizing denture base resins.

In an attempt to simulate the plasticizing effect that saliva has on denture polymers researchers include in their experimental protocol a period of water immersion prior to testing the strength of denture polymers [106,108–110]. There seem to be little agreement as to how long denture polymers should be immersed prior to their mechanical testing. Although the international standard guidelines [119] points to 50 h of water immersion Takahashi et al. [110] suggested that the equilibrium strength of some denture polymers may well exceed 30 days. Although they recommend a 4-month water immersion protocol, the mainly water sorption occurs during the initial 14 days [108–110].

Chewing may also be responsible for changes in the viscoelastic properties of the materials. Muraoka et al. [120] showed that cyclic loading influenced the viscoelastic properties especially the delayed deformation of acrylic based soft lining materials. The decrease of delayed deformation indicated reduced stress distribution effects of soft lining materials. Moreover the water absorption per surface area was suggested to increase after cyclic loading [120].

Clinical changes in the viscoelasticity of acrylic based soft lining materials are characterized by a more rapid and increase reduction on compliance than *in vitro* media such as water, artificial saliva or denture cleansers. A possible explanation for these differences is a solvent effect due to dietary [40].

Mixtures of ethanol and water are considered solvents which serve as food simulating liquids [121]. The monomer matrix is hydrophilic and absorbs substantial amounts of ethanol and water molecules. The solvent penetrates the resin matrix that becomes less hard and less fracture resistant [121]. Nevertheless Jepson et al. [40] found that none of the dietary simulating solvents showed clinical changes in compliance except the corn oil or heptanes that simulate the effect of fatty foods.

3.2.2. *Bond strength between denture base and reline resins*

Degradation processes not only changes the inner properties of the resins but also affects the bond strength between the denture base resin and the relining material [111]. Polyzois [122] found a statistically significant reduction in bond strength between soft lining materials and denture base resins after 4 months in water storage. They reported that this reduction is the result of absorption of water and consequence of swelling and stress build up at the bond interface. This fact is corroborated by the weak bond between the PMMA based net of the denture base resin and non-MMA based net of the reline resin. This bond is achieved by penetration and diffusion of the reline monomer into the denture base resin and formation of an interpenetrating polymer network. MMA modified

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molecules are largest and heavier than pure MMA molecules and that fact could affect bonding. When the material swells, not only stress builds between the bonding surfaces but also the viscoelastic properties of the liners changes. The material becomes brittle and transfers the external loads to the bond area.

Other studies have similar results [106,109,110,123] showing a decrease in tensile bond strength of relined denture base resins submitted to water storage. Cucci et al. [105] found that tensile bond strength between hard reline and denture base resins can be affected by 30 days of storage in water but not in all the resins. Nevertheless other researchers like Minami et al. [39] showed that shear bond strengths of autopolymerizing resin to denture base resins were not significantly influenced by water content of the denture base polymer. Also El-Hadary and Drummond [124] found no difference on tensile bond strength of a acrylic based soft lining material submitted to 12 weeks storage. A failure in bonding of relining materials can harbor bacteria, promote staining and cause complete delamination and failure of the lining. A weak bond will also decrease the strength of the denture and cause fractures [109].

The temperature also has effects on the bond strength of a lining material to the denture base resin. Minami et al. [39] showed that bond strengths of autopolymerizing resin to denture base resins are influenced by thermal cycling.

Water absorption has been reported to reach saturation earlier with a higher water temperature [125]. Once the network is saturated with water and becomes softened the polymer structures stabilizes and there is no further reduction in properties [109]. Dootz et al. [117] reported highest values of tensile bond strengths for resilient lining materials after thermocycling. Other researchers [111,116,126] had the same kind of results and associated it with the continual polymerization of the material or with the release of plasticizer agents during thermal cycling. The increase in the rigidity of the material compensates the decrease in tensile strength caused by water sorption allowing an increase of the shear tensile bond between the liner and the acrylic resin.

4. Unexplored topics and areas for future research

Biodegradation of acrylic based resins under the oral environment has been so far uncompleted studied. Some questions that need to be investigated include: which enzymes are involved in the *in vivo* process of acrylic resins degradation? What are their co-factors? Is the saliva of one individual more likely to degrade certain materials than that from another person? What is the level of the different products *in vivo*?

A gap in the published literature exists regarding *in vitro* studies that allow a good knowledge of the biodegradation mechanisms and its consequences. Improvements in the experimental design should be done in order to better simulate the intraoral conditions. Using artificial saliva that include in its composition salivary enzymes and mucines and extending the studies in time will allow a more complete evaluation of the biodegradation process. Analytical techniques as gas chromatography/mass spectrometry (GC–MS) that provides means of identifying and quantifying more accurately the products of biodegradation at low concentrations should be more often used in the studies.

Basic research on the effect of biodegradation products on cells should proceed. The detailed mechanisms necessary to initiate apoptosis or necrosis by the materials remain to be elucidated [51]. The mechanism of interaction of MMA monomers with cell membranes remains unknown with respect to cytotoxicity and calcium release [86]. The MMA effect on dental pulp cells, in spite of its great clinical relevance, has rarely been studied [92]. Possible involvement of oxidative enzymes in cytotoxcity induced by MMA remains to be studied [88]. The biological impact of acrylic based resins biodegradation on cells caused by salivary enzymes, mucines or bacteria has not been addressed so far.

The clinical consequences of biodegradation are still poorly understood. Assessing what may be the extent of the biological effects as a result of the long-term release of biodegradation products still requires extensive study. The gap that exists between the results published by research laboratories and clinical reports should be shortened. Further well-controlled clinical studies are necessary to improve the knowledge about materials biocompatibility in intraoral conditions [7] including their potential to cause chronic local adverse effects or/and systemic side effects over time.

Evaluation of biodegradation aspects of acrylic based resins should be widened and considered not only as negative aspects regarding loss of mechanical properties and adverse toxic effects but can also be explored towards a positive interaction with the oral environment. The incorporation of products like antioxidant molecules intending to enhance the biocompatibility of the materials has been recently explored with promising results [89]. The use of acrylic based resins as drug delivery polymer systems could be an innovative new strategy for extending the use of these materials in the clinical dental practice.

5. Conclusions

The following conclusions are draw from this review:

1. Acrylic based resins are intensively used in dentistry practice as restorative, liners or as denture base materials. These substances are made by polymerization of methacrylate related monomers. Materials can be classified as chemical, heat or light polymerizing depending on the factor that initiates the polymerization reaction.
2. Increasing concern arises regarding the safe clinical application of these materials due to their biodegradation under the oral environment.
3. The number and diversity of processes by which acrylic based resins may be degraded in the oral cavity are huge and are now recognized as a complex interplay of interactions. Causes for biodegradation comprise several factors such as saliva characteristics, chewing or thermal and chemical dietary changes.
4. Consequences of materials biodegradation refer mainly to the release of potential toxic compounds from the polymer network and changes in materials physical and mechanical properties.

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5. There is a sizeable literature on *in vitro* release studies concerning the elution of residual monomers, mainly MMA, in water. Considerable less studies use ethanol or artificial saliva as the leaching media. Experiments using human saliva are rare and few *in vivo* studies have been reported.
6. Products of acrylic based resins biodegradation have been suspected of having undesirable biological effects particularly as xenoestrogens and allergens. Reviewed cell based studies indicate that different compounds eluted from acrylic base resins (MMA and derivatives, phthalates, formaldehyde) have the potential to induce cytotoxicity, genotoxicity, change in cytokine/growth factor expression and oxidative stress on permanent and primary cells.
7. Degradation processes not only changes the inner properties of the resins but also affects the bond strength between the denture base resin and the relining material.
8. There is opportunity for future research in different areas related to the evaluation of acrylic based resins biodegradation. This will lead to a more concise definition of biocompatibility issues related to these dental materials. The information acquired from such studies can also provide investigators with alternative polymeric chemistries that can be used in a new generation of materials able to induce favorable reactions in the living tissues.

REFERENCES

[1] Hong G, Murata H, Li Y, Sadamori S, Hamada T. Influence of denture cleansers on the color stability of three types of denture base acrylic resin. J Prosthet Dent 2009;101:205–13.
[2] Sadamori S, Siswomihardjo W, Kameda K, Saito A, Hamada T. Dimensional changes of relined denture bases with heat cured, microwave-activated, autopolymerizing, and visible light cured resins. A laboratory study. Aust Dent J 1995;40:322–6.
[3] Azzarri MJ, Cortizoa MS, Alessandrini JL. Effect of the curing conditions on the properties of an acrylic denture base resin microwave-polymerised. J Dent 2003;31:463–8.
[4] León BLT, Del Bel Cury AA, Rodrigues Garcia RCM. Loss of residual monomer from resilient lining materials processed by different methods. Rev Odonto Ciênc 2008;23:215–9.
[5] Bayraktar G, Guvener B, Bural C, Uresin Y. Influence of polymerization method, curing process, and length of time of storage in water on the residual methyl methacrylate content in dental acrylic resins. J Biomed Mater Res B: Appl Biomater 2006;76:340–5.
[6] Urban VM, Machado AL, Vergani CE, Giampaolo ET, Pavarina AC, Almeida FG, Cass QB. Effect of water-bath post-polymerization on the mechanical properties, degree of conversion, and leaching of residual compounds of hard chairside reline resins. Dent Mater 2009;25:662–71.
[7] Celebi N, Yuzugullu B, Canay S, Yucel U. Effect of polymerization methods on the residual monomer level of acrylic resin denture base polymers. Polym Adv Technol 2008;19:201–6.
[8] Braden M. Some aspects of the chemistry and physics of dental resins. Adv Dent Res 1988;2:93–7.
[9] Sawtell RM, Downes S, Patel MP, Clarke RL, Braden M. Heterocyclic methacrylates for clinical applications-further studies of water sorption. J Mater Sci Mater Med 1997;8:667–74.
[10] Mendonça MJ, Machado AL, Giampaolo ET, Pavarina AC, Vergani CE. Weight loss and surface roughness of hard chairside reline resins after toothbrushing: influence of postpolymerization treatments. Int J Prosthodont 2006;19:281–7.
[11] Parker S, Braden M. Formulation of tissue conditioners. Biomaterials 1990;11:579–84.
[12] Munksgaard EC. Plasticizers in denture soft-lining materials: leaching and biodegradation. Eur J Oral Sci 2005;113:166–9.
[13] Gutierrez-Villarreal MH, Rodríguez-Velazquez J. The effect of citrate esters as plasticizers on the thermal and mechanical properties of poly(methyl methacrylate). J Appl Polym Sci 2007;105:2370–5.
[14] Hong G, Murata H, Hamada T. Relationship between plasticizer content and tensile bond strength of soft denture liners to a denture base resin. Dent Mater J 2004;23:94–9.
[15] Faltermeier A, Rosentritt M, Müssig D. Acrylic removable appliances: Comparative evaluation of different postpolymerization methods. Am J Orthod Dentofacial Orthop 2007;131:301.e16–22.
[16] Labban N, Song F, Al-Shibani N, Windsor LJ. Effects of provisional acrylic resins on gingival fibroblast cytokine/growth factor expression. J Prosthet Dent 2008;100:390–7.
[17] Ebadian B, Razavi M, Soleimanpour S, Mosharraf R. Evaluation of tissue reaction to some denture-base materials: an animal study. J Contemp Dent Pract 2008;1:67–74.
[18] Boeckler AF, Morton D, Poser S, Dette KE. Release of dibenzoyl peroxide from polymethyl methacrylate denture base resins: an in vitro evaluation. Dent Mater 2008;24:1602–7.
[19] Ferracane JL. Hygroscopic and hydrolytic effects in dental polymer networks. Dent Mater 2006;22:211–22.
[20] Santerre JP, Shajii L, Leung BW. Relation of dental composite formulations to their degradation and the release of hydrolyzed polymeric-resin-derived products. Crit Rev Oral Biol Med 2001;12:136–51.
[21] Kawahara T, Nomura Y, Tanaka N, Teshima W, Okazaki M, Shintani H. Leachability of plasticizer and residual monomer from commercial temporary restorative resins. J Dent 2004;32:277–83.
[22] Braden M, Causton BE, Clarke RL. Diffusion in water in composite filling materials. J Dent Res 1976;55:730–2.
[23] Kalachandra S, Turner DT. Water sorption of polymethacrylate networks.bis-GMA/TEGDM copolymers. Biomed Mater Res 1987;21:329–38.
[24] Sideridou I, Achilias DS, Spyroudi C, Karabela M. Water sorption characteristics of light-cured dental resins and composites based on Bis-EMA/PCDMA. Biomaterials 2004;25:367–76.
[25] Santerre JP, Shajii L, Tsang H. Biodegradation of commercial dental composites by cholesterol esterase. J Dent Res 1999;78:1459–68.
[26] Finer Y, Santerre JP. Salivary esterase activity and its association with the biodegradation of dental composites. J Dent Res 2004;83:22–6.
[27] Jaffer F, Finer Y, Santerre JP. Interactions between resin monomers and commercial composite resins with human saliva derived esterases. Biomaterials 2002;23:1707–9.
[28] Lin BA, Jaffer F, Duff MD, Tang YW, Santerre JP. Identifying enzyme activities within human saliva which are relevant to dental resin composite biodegradation. Biomaterials 2005;26:4259–64.
[29] Yourtee DM, Smith RE, Russo KA, Burmaster S, Cannon JM, Eick JD, Kostoryz EL. The stability of methacrylate biomaterials when enzyme challenged: kinetic and systematic evaluations. J Biomed Mater Res 2001;57:522–31.

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[30] Larsen IB, Munksgaard EC. Effect of human saliva on surface degradation of composite resins. Scand J Dent Res 1991;99:254–61.
[31] Larsen IB, Freund M, Munksgaard EC. Change in surface hardness of Bis-GMA/TEGDMA polymer due to enzymatic action. J Dent Res 1992;71:1851–3.
[32] Willershausen B, Callaway A, Ernst CP, Stender E. The influence of oral bacteria on the surfaces of resin-based dental restorative materials: an *in vitro* study. Int Dent J 1999;49:231–9.
[33] Drummond JL. Degradation, fatigue and failure of resin dental composite materials. J Dent Res 2008;87:710–9.
[34] Roulet JF. Degradation of dental polymers. Basel: Karger; 1987.
[35] Jones DW, Sutow EJ, Hall GC, Tobin WM, Graham BS. Dental soft polymers: plasticizer composition and leachability. Dent Mater 1988;4:1–7.
[36] Graham BS, Jones DW, Suttow EJ. An in vivo and in vitro study of the loss of plasticizer from soft polymer-gel materials. J Dent Res 1991;70:870–3.
[37] Kournetas N. Impact of artificial ageing process on the wear resistance of dental materials. MA Thesis, Tübingen; 2005.
[38] Neppelenbroek KH, Pavarina AC, Gomes MN, Machado AL, Vergani CE. Bond strength of hard chairside reline resins to a rapid polymerizing denture base resin before and after thermal cycling. J Appl Oral Sci 2006;14:436–42.
[39] Minami H, Suzuki S, Minesaki Y, Kurashige H, Tanaka T. In vitro evaluation of the influence of repairing condition of denture base resin on the bonding of autopolymerizing resins. J Prosthet Dent 2004;91:164–70.
[40] Jepson NJA, McGill JT, McCabe JF. Influence of dietary simulating solvents on the viscoelasticity of temporary soft lining materials. J Prosthet Dent 2000;83:25–31.
[41] Gonçalves TS, Menezes LM, Silva LEA. Residual monomer of autopolymerized acrylic resin according to different manipulation and polishing methods. Angle Orthod 2008;78:722–7.
[42] Koda T, Tsuchiya H, Yamauchi M, Ohtani S, Takagi N, Kawano J. Leachability of denture-base acrylic resins in artificial saliva. Dent Mater 1990;6:13–6.
[43] Tsuchiya H, Hoshino Y, Tajima K, Takagi N. Leaching and cytotoxicity of formaldehyde and methylmethacrylate from acrylic resin denture base materials. J Prosthet Dent 1994;71:618–24.
[44] Kedjarune U, Charoenworaluk N, Koontongkaew S. Release of methyl methacrylate from heat-cured and autopolymerized resins: cytotoxicity testing related to residual monomer. Aust Dent J 1999;44:25–30.
[45] Vallittu PK, Alakujala P. Residual monomer content and its release into water denture materials. Dent Mater 1995;11:338–42.
[46] Viljanen EK, Langer S, Skrifvars M, Vallittu PK. Analysis of residual monomers in dendritic methacrylate copolymers and composites by HPLC and headspace-GC/MS. Dent Mater 2006;22:845–51.
[47] Zissis A, Yannikakis S, Polyzois G, Harrison A. A long term study on residual monomer release from denture materials. Eur J Prosthodont Restor Dent 2008;16:81–4.
[48] Mello JAN, Braun KO, Rached RN, Del Bel Cury AA. Reducing the negative effects of chemical polishing in acrylic resins by use of an additional cycle of polymerization. J Prosthet Dent 2003;89:598–602.
[49] Filho RR, Paula LV, Costa VC, Seraidarian PI. Avaliação de monômero residual em resinas acrílicas de uso ortodôntico e protético: análise por espectroscopia. R Dental Press Ortodon Ortop Facial 2007;12:96–104.
[50] Kawaguchi M, Takahashi Y, Fukushima T, Habu T. Effect of light-exposure duration on the amount of leachable monomers from light-activated reline material. J Prosthet Dent 1996;75:183–7.
[51] Lai YL, Chen YT, Lee SY, Shieh TM, Hung SL. Cytotoxic effects of dental resin liquids on primary gingival fibroblasts and periodontal ligament cells in vitro. J Oral Rehabil 2004;31:1165–72.
[52] Sofou A, Tsoupi I, Karayannis M, Owall B. Determination of residual monomers released from soft lining materials with the use of HPLC. Pak J Anal Environ Chem 2007;8:41–52.
[53] Brozek R, Rogalewicz R, Koczorowski R, Voelkel A. The influence of denture cleansers on the release of organic compounds from soft lining materials. J Environ Monit 2008;10:770–4.
[54] Stafford GD, Brooks SC. The loss of residual monomer from acrylic orthodontic resins. Dent Mater 1985;1:135–8.
[55] Imazato S, Horikawa D, Ogata K, Kinomoto Y, Ebisu S. Responses of MC3T3-E1 cells to three dental resin-based restorative materials. J Biomed Mater Res A 2006;76: 765–72.
[56] Hashimoto Y, Kawaguchi M, Miyazaki K, Nakamura M. Estrogenic activity of tissue conditioners in vitro. Dent Mater 2003;19:341–6.
[57] Tsuchiya H, Hoshino Y, Kato H, Takagi N. Flow injection analysis of formaldehyde leached from denture-base acrylic resins. J Dent 1993;21:240–3.
[58] Vallittu PK. The effect of surface treatment of denture acrylic resin on the residual monomer content and its release into water. Acta Odontol Scand 1996;54:188–92.
[59] Sofou A, Tsoupi I, Emmanouil J, Karayannis M. HPLC determination of residual monomers released from heat-cured acrylic resins. Anal Bioanal Chem 2005;381:1336–46.
[60] Baker S, Brooks SC, Walker DM. The release of residual monomeric methyl methacrylate from acrylic appliances in the human mouth: an assay for monomer in saliva. J Dent Res 1988;67:1295–9.
[61] Lygre H, Solheim E, Gjerdet NR, Berg E. Leaching of organic additives from dentures in vivo. Acta Odontol Scand 1993;51:45–51.
[62] Lygre H, Klepp KN, Solheim E, Gjerdet NR. Leaching of additives and degradation products from cold-cured orthodontic resins. Acta Odontol Scand 1994;52:150–6.
[63] Sadamori S, Kotani H, Hamada T. The usage period of dentures and their residual monomer contents. J Prosthet Dent 1992;68:374–6.
[64] Lefebvre CA, Schuster GS, Marr JC, Knoernschild KL. The effect of pH on the cytotoxicity of eluates from denture base resins. Int J Prosthodont 1995;8:122–8.
[65] Keyf FA, Keyf AI. Harmful effects of methylmethacrylate and formaldehyde from acrylic resin denture base materials. Saudi Dent J 1998;10:23–8.
[66] Weaver RE, Goebel WM. Reactions to acrylic resin dental prostheses. J Prosthet Dent 1980;43:138–42.
[67] Bohnenkamp DM. Traumatic stomatitis following an intraoral denture reline: a clinical report. J Prosthet Dent 1996;76:113–4.
[68] Ruiz-Genao DP, Moreno de Vega MJ, Sanchez Perez J, Garcia-Diez A. Labial edema due to an acrylic dental prosthesis. Contact Dermatitis 2003;48:273–4.
[69] Giunta J, Zablotsky N. Allergic stomatitis caused by self-polymerizing resin. Oral Surg Oral Med Oral Pathol 1976;41:631–7.
[70] Lunder T, Rogl-Butina M. Chronic urticaria from an acrylic dental prosthesis. Contact Dermatitis 2000;43:232–3.
[71] Leggat PA, Kedjarune U. Toxicity of methylmethacrylate in dentistry. Int Dent J 2003;53:126–31.
[72] Gonçalves TS, Morganti MA, Campos LC, Rizzatto SM, Menezes LM. Allergy to auto-polymerized acrylic resin in

Please cite this article in press as: Bettencourt AF, et al. Biodegradation of acrylic based resins: A review. Dent Mater (2010), doi:10.1016/j.dental.2010.01.006

an orthodontic patient. Am J Orthod Dentofacial Orthop 2006;129:431–5.
[73] Aalto-Korte K, Alanko K, Kuuliala O, Jolanki R. Methacrylate and acrylate allergy in dental personnel. Contact Dermatitis 2007;57:324–30.
[74] Jorge JH, Giampaolo ET, Machado AL, Vergani CE. Cytotoxicity of denture base acrylic resins: a literature review. J Prosthet Dent 2003;90:190–3.
[75] Goldibi F, Asghari G. The level of residual monomer in acrylic denture base materials. Res J Biol Sci 2009;4:244–9.
[76] Shuster GS, Lefebvre CA, Dirksen TR, Knoernschild KL, Caughmann GB. Relationship between denture base resin cytotoxicity and cell lipid metabolism. Int J Prosthodont 1995;8:580–6.
[77] Vale FM, Castro M, Monteiro J, Couto FS, Pinto R, Giao Toscano Rico JM. Acrylic bone cement induces the production of free radicals by cultured human fibroblasts. Biomaterials 1997;18:1133–5.
[78] Sheridan PJ, Koka S, Ewoldsen NO, Lefebvre CA, Lavin MT. Cytotoxicity of denture base resins. Int J Prosthodont 1997;10:73–7.
[79] Cimpan MR, Matre R, Cressey LI, Tysnes B, Lie SA, Gjertsen BT, Skaug N. The effect of heat- and auto-polymerized denture base polymers on clonogenicity, apoptosis, and necrosis in fibroblasts: denture base polymers induce apoptosis and necrosis. Acta Odontol Scand 2000;58: 217–28.
[80] Gough JE, Downes S. Osteoblast cell death on methacrylate polymers involves apoptosis. J Biomed Mater Res 2001;57:497–505.
[81] Huang FM, Tai KW, Hu CC, Chang YC. Cytotoxic effects of denture base materials on a permanent human oral epithelial cell line and on primary human oral fibroblasts in vitro. Int J Prosthodont 2001;14:439–43.
[82] Ciapetti G, Granchi D, Savarino L, Cenni E, Magrini E, Baldini N, Giunti A. In vitro testing of the potential for orthopedic bone cements to cause apoptosis of osteoblast-like cells. Biomaterials 2002;23:617–27.
[83] Yang HW, Chou LSS, Chou MY, Chang YC. Assessment of genetic damage by methyl methacrylate employing in vitro mammalian test system. Biomaterials 2003;24:2909–14.
[84] Jorge JH, Giampaolo ET, Vergani CE, Machado AL, Pavarina AC, Carlos IZ. Effect of post-polymerization heat treatments on the cytotoxicity of two denture base acrylic resins. J Appl Oral Sci 2006;14:203–7, javascript:AL_get(this, 'jour', 'J Appl Oral Sci.').
[85] Campanha NH, Pavarina AC, Giampaolo ET, Machado AL, Carlos IZ, Vergani CE. Cytotoxicity of hard chairside reline resins: effect of microwave irradiation and water bath postpolymerization treatments. Int J Prosthodont 2006;19:195–201.
[86] Atsumi T, Fujisawa S, Tonosaki K. (Meth)acrylate monomer-induced cytotoxicity and intracellular Ca^{2+} mobilization in human salivary gland carcinoma cells and human gingival fibroblast cells related to monomer hydrophobicity. Biomaterials 2006;27:5794–800.
[87] Bettencourt A, Fernandes A, Oliveira N, Monteiro J, Calado A, Castro M. Evaluation of cytotoxicity and oxidative stress induced by acrylic bone cement in Raw 264.7 macrophages. Free Radic Biol Med 2007;43(Suppl. 1):S44.
[88] Hattori N, Suzuki T, Jinno S, Okeya H, Ishikawa A, Kondo C, Hayashi T, Ito M, Kanamori T, Kawai T, Noguchi T. Methyl methacrylate activates the *Gsta1* promoter. J Dent Res 2008;87:1117–21.
[89] Att W, Yamada M, Kojima N, Ogawa T. N-Acetyl cysteine prevents suppression of oral fibroblast function on poly(methylmethacrylate) resin. Acta Biomater 2009;5:391–8.
[90] Moreau MF, Chappard D, Lesourd M, Montheard JP, Basle MF. Free radicals and side products released during methylmethacrylate polymerization are cytotoxic for osteoblastic cells. J Biomed Mater Res 1998;40:124–31.
[91] Kim SH, Kim SS, Kwon O, Sohn KH, Kwack SJ, Choi YW, Han SY. Effects of dibutyl phthalate and monobutyl phthalate on cytotoxicity and differentiation in cultured rat embryonic limb bud cells; protection by antioxidants. J Toxicol Environ Health A 2002;65:461–72.
[92] Kojima N, Yamada M, Paranjpe A, Tsukimura N, Kubo K, Jewett A, Ogawa T. Restored viability and function of dental pulp cells on poly-methylmethacrylate (PMMA)-based dental resin supplemented with N-acetyl cysteine (NAC). Dent Mater 2008;24:1686–93.
[93] Ishikawa A, Jinno S, Suzuki T, Hayashi T, Kawai T, Mizuno T, Mori T, Hattori M. Global gene expression analyses of mouse fibroblast L929 cells exposed to IC50 MMA by DNA microarray and confirmation of four detoxification genes' expression by real-time PCR. Dent Mater J 2006;25: 205–13.
[94] Schweikl H, Schmalz G, Spruss T. The induction of micronuclei *in vitro* by unpolymerized resin monomers. J Dent Res 2001;80:1615–20.
[95] Schweikl H, Spagnuolo G, Schmalz G. Genetic and cellular toxicology of dental resin monomers. J Dent Res 2006;85:870–7.
[96] Yoshii E. Cytotoxic effects of acrylates and methacrylates: relationships of monomer structures and cytotoxicity. J Biomed Mater Res A 1997;37:517–24.
[97] Autian J. Structure–toxicity relationships monomers. Environ Health Perspect 1975;11:141–52.
[98] Lawrence WH, Bass GE, Purcell WP, Autian J. Use of mathematical models in the study of structure–toxicity relationships of dental compounds. Esters of acrylic and methacrylic acids. J Dent Res 1972;51:526–35.
[99] Bass GE, Lawrence WH, Purcell WP, Autian J. Further evaluation of a quantitative mathematical model for predicting acute toxicity of acrylate and methacrylate esters. J Dent Res 1974;53:756.
[100] Dillingham EO, Laurence WH, Autian J. Acrylate and methacrylate esters: Relationship of hemolytic activity and *in vivo* toxicity. J Biomed Mater Res 1983;17:945–57.
[101] Kleinsasser NH, Wallner BC, Kastenbauer ER, Weissacher H, Harréus UA. Genotoxicity of di-butyl-phthalate and di-iso-butyl-phthalate in human lymphocytes and mucosal cells. Teratog Carcinog Mutagen 2001;21:189–96.
[102] Masuki K, Nomura Y, Bhawal UK, Sawajiri M, Hirata I, Nahara Y, Okazaki M. Apoptotic and necrotic influence of dental resin polymerization initiators in human gingival fibroblasts cultures. Dent Mater J 2007;26:861–9.
[103] Woefel JB, Paffenbarger GC, Sweeney WT. Some physical properties of organic denture base materials. J Am Dent Assoc 1963;67:489–504.
[104] Dixon DL, Breeding LC, Ekstrand KG. Linear dimensional variability of three denture base resins after processing and in water storage. J Prosthet Dent 1992;68:196–200.
[105] Cucci ALM, Rached RN, Giampaolo ET, Vergani CE. Tensile bond strengths of hard chairside reline resins as influence by water storage. J Oral Rehabil 1999;26:631–4.
[106] Mese A, Guzel KG. Effect of storage duration on the hardness and tensile bond strength of silicone- and acrylic resin-based resilient denture liners to a processed denture base acrylic resin. J Prosthet Dent 2008;99:153–9.
[107] Dixon DL, Ekstrand KG, Breeding LC. The transverse strength of three denture base resins. J Prosthet Dent 1991;66:510–3.
[108] Takahashi Y, Chai J, Kawaguchi M. Effect of water sorption on the resistance to plastic deformation of a denture base

Please cite this article in press as: Bettencourt AF, et al. Biodegradation of acrylic based resins: A review. Dent Mater (2010), doi:10.1016/j.dental.2010.01.006

material relined with four different denture reline materials. Int J Prosthodont 1998;11:49–54.
[109] Takahashi Y, Chai J, Kawaguchi M. Equilibrium strengths of denture polymers subjected to long-term water immersion. Int J Prosthodont 1999;12:348–52.
[110] Takahashi Y, Chai J, Kawaguchi M. Strength of relined denture base polymers subjected to long-term water immersion. Int J Prosthodont 2000;13:205–8.
[111] Sato T, Takahashi H, Hongo T, Hayakawa I. Effect of degradation of denture base resin on bond strength to relining resins. Dent Mater J 2007;26:89–95.
[112] Fuji K. Fatigue properties of acrylic denture base resins. Dent Mater J 1989;8:243–59.
[113] Rawls H. Dental polymers. In: Anusavice KJ, editor. Phillips' science of dental materials. 11th ed. St. Louis: Elsevier Science; 2003. pp. 143–169 [Chapter 7].
[114] Koran III A. Prosthetic applications of polymers. In: Craig R, Powers J, editors. Restorative dental materials: Mosby. 11th ed. 2002. pp. 635–681 [Chapter 21].
[115] Braden M, Wright PS. Water absorption and water solubility of soft lining materials for acrylic dentures. J Dent Res 1983;62:764–8.
[116] Qudah S, Huggett R, Harrison A. The effect of thermocycling on the hardness of soft lining materials. Quintessence Int 1991;22:575–80.
[117] Dootz ER, Karon A, Craig RG. Physical property comparison of 11 soft denture lining materials as a function of accelerated aging. J Prosthet Dent 1993;69:114–9.
[118] Arima T, Murata H, Hamada T. Properties of highly cross-linked autopolymerizing reline acrylic resins. J Prosthet Dent 1995;73:55–9.
[119] International Organization for Standardization. Specification 1567: denture base polymers. 2nd ed. Switzerland: ISO; 1999.
[120] Muraoka G, Takahashi H, Hayakawa I. Effects of cyclic loading on viscoelastic properties of soft lining materials. Dent Mater J 2003;22:251–61.
[121] Ferracane JL, Berge HX. Fracture toughness of experimental dental composites aged in ethanol. J Dent Res 1995;74:1418–23.
[122] Polyzois GL. Adhesion properties of resilient lining materials bonded to light-cured denture. J Prosthet Dent 1992;68:854–8.
[123] Aydin AK, Terzioglu H, Akinay AE, Ulubayram K, Hasirci N. Bond strength and failure analysis of lining materials to denture resin. Dent Mater 1999;15:211–8.
[124] El-Hadary A, Drummond JL. Comparative study of water sorption, solubility and tensile bond strength of two soft lining materials. J Prosthet Dent 2000;83:356–61.
[125] Braden M. The absorption of water by acrylic resins and other materials. J Prosthet Dent 1964;14:307–16.
[126] Léon BLT, del Bel Cury AA, Garcia RCMR. Water sorption, solubility and tensile bond strength of resilient denture lining materials polymerized by different methods after thermal cycling. J Prosthet Dent 2005;93:282–7.

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