A comparative in-vitro analysis of peel bond strengths of chair side resilient reline materials to conventional, additive, and subtractive manufactured denture bases.

by

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Abstract

A comparative in-vitro analysis of peel bond strengths of chair side resilient reline materials to conventional, additive, and subtractive manufactured denture bases.

<u>Purpose:</u> To analyze peel bond strengths between three different denture bases and different classes of resilient reline materials.

<u>Methods:</u> Denture base acrylic samples were fabricated using heat cured PMMA (ProBase Hot); according to manufacturer's instructions in a custom fabricated stainless-steel mould to create rectangular acrylic blocks of 65 X10 X 3mm. Subtractive CAD/ CAM denture base samples were created using a band saw by sectioning prepolymerized PMMA pucks (IvoBase CAD) in test sample dimensions. For additive CAD/CAM denture base samples, first a prototype sample was designed using a free CAD software program (Meshmixer) and then 3D printed with a Form 3B printer, using a photopolymerizable denture base resin (Denture base RP). Post processing of 3D printed samples was carried out as per manufacturer's recommendations. Test surfaces were prepared following a standardised protocol of polishing and washing. These samples were then relined with silicone-based liner (Tokuyama Sofreliner Tough S), a plasticized acrylic liner (Coe Soft); and for the second part of the study with a tissue conditioner (Coe Comfort). It was ensured that bonding was limited to only 22 mm of prepared test surface while remaining 43 mm of sample surface was left unbonded to allow peeling during testing. Samples were loaded into a Landmark® Servohydraulic testing machine and then peeled at crosshead speeds of 20 mm/min for resilient liners and 50 mm/min for tissue conditioner, until failure occurred.

<u>Results</u>: In first part of study, results show, that type of denture base (p= 0.5274) and the 10-day water storage (p= 0.58073) had no significant effect on the peel bond strength values. Type of resilient liner did significantly affect the peel bond strength. Sofreliner Tough S (Mean1.6 ± 0.17MPa) had significantly higher bond strengths than Coe Soft (Mean 0.2 ± 0.10 MPa). In second part of study, results show, that type of denture base (P value = 0.00728) and the 10-day water storage (P value = 0.00278); had significant effect on the peel bond strength values of Coe Comfort. At 0-days, Coe Comfort showed highest mean peel bond strength with Probase Hot (Mean 0.28244 ± 0.20387 MPa). At 10-days of water immersion, Coe Comfort showed highest

peel bond strength with Formlabs Denture Base RP (Mean 0.05599 ± 0.02177 MPa). There may be a generalized trend for peel bond strength reduction in both resilient liners and tissue conditioner with 10-day water immersion.

Conclusion: Tokuyama Sofreliner Tough S has much higher peel bond strength as compared to Coe-Soft resilient liner. Peel bond strength of Coe Comfort is significantly affected by type of denture base and water immersion.

Dedication

This thesis is dedicated to my wonderful wife, Reema. All my achievements and this thesis is a fruit of your unending love, unwavering support, and constant belief through out all my eccentricities, quirks and mood swings during residency and life, in general.

To my wonderful daughters, Liesha, Purvi and Heena, you are the most amazing children a parent could ask for and you all inspire me to be a better person every single day.

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Nomenclature

CRDP	Complete Removable Dental Prosthesis
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CECD	Computer Engineered Complete Denture
3DP	3-Dimensional Printing
STL	Standard Tessellation Language
PMMA	Polymethyl Methacrylate
PEMA	Polyethyl Methacrylate
AC	Acetal Denture Base
PA	Polyamide Denture Base
RRR	Residual Ridge Resorption
RTV	Room Temperature Vulcanized Silicone-Based Liners
HTV	High Temperature Vulcanized Silicone-Based Liners
ABLTDL	Acrylic Based Long-Term Soft Denture Lining Material
SBLTDL	Silicone Based Long-Term Soft Denture Lining Material

Table of Contents

List of Figures

List of Tables

CHAPTER 1

1.1 Introduction and Background

Complete edentulism is a highly prevalent oral disease worldwide and complete dentures have been a traditional and a common choice to treat edentulism (Emami et al, 2013). There has been a steady decline in prevalence of complete edentulism mainly due to increased awareness, accessibility to oral health care and advent in preventive care but this decline is partially offset with increase in population (Slade et al, 2014). It has been estimated there will be tens of millions of newly edentulous people requiring complete denture therapy in US by 2050 (Douglas et al, 2002).

Conventional denture fabrication procedures utilize polymerization of polymethyl methacrylate (PMMA) into removable complete dentures. These conventional denture fabrication methods are well established, much researched, and have not changed in over 80 years (Wimmer et al, 2016). There was however a paradigm shift with introduction of computer aided designing (CAD) and computer aided manufacturing (CAM) technologies in fabrication of conventional removable dental prosthesis (CRDP) by Maeda et al in 1994. Since their introduction digital dentures have exploded in popularity. Purported benefits of CAD/CAM complete dentures over conventionally processed PMMA CRDPs include, but are not limited to; higher strength, lower distortion and much better mechanical properties with monolithic milled denture (Bilgin et al, 2016), reduced incidence of microbial colonization in milled denture bases (Bilgin et al, 2016), significantly increased denture retention, at least in the short term (Kattadiyil et al, 2015), significantly reduced number of post-delivery denture adjustment visits in first year (Kattadiyil et al, 2017, Bidra et al, 2016) and reduced costs due to savings in chair and lab times (Srinivasan et al, 2019).

Kattadiyil et al, (2017) in a systematic review coined the term computer engineered complete dentures (CECD) and concluded that CECDs have favorable clinical outcomes if proper patient selection was made. CECD manufacturing can involve either digital designing or digital fabrication only or may utilize both. Additionally, CECD fabrication could be achieved either through subtractive or additive manufacturing (Kattadiyil et al, 2017)

Denture base adaptation and good peripheral border seal have been described as some of the most important factors contributing to denture retention (Darevell et al, 2000). However, it is important to note that soft tissue contours change through out the life of denture service as a result of continued resorption of residual ridge (Tallgren et al, 2003, Atwell et al, 1971). This necessitates continuous alteration of intaglio surface of the complete removable dental prosthesis (CRDP) to maintain intimate contact with denture supporting tissues (Darevell et al, 2000). Refitting of the intaglio surface of the denture prosthesis to ensure continuous harmonious fit is thus a critical component of complete denture service (Zarb et al, 2013).

This refitting can be easily achieved through a reline procedures. Relining involves additions to intaglio surface of an existing complete denture to refit the intaglio surface to the time dependent altered state of denture bearing tissues (Zarb et al, 2013). It is important to note though that for reline a denture needs to be clinically acceptable. One can not reline and should not attempt to reline a clinically inadequate CRDP (Ortman et al, 1975).

Denture reline procedure is a relatively quick and cheaper procedure which can be accomplished either chair side (direct) or laboratory processed (indirect), allowing continued use of existing denture. Reline procedure does have its own set of multiple drawbacks with loss of adhesion being the most important and common reason for failure (Kreve et al, 2019).

Complete denture reline procedure has additional benefits other than increasing the service life of a CRDP. Relines can also be used as a diagnostic adjunctive, as a tissue conditioner, for pain relief, to make functional impression and for retention of maxillofacial prosthetic appliances into surgical and acquired defects (Zarb et al, 2013).

Resilient denture liners are most commonly available in 2 types: silicone based and plasticized acrylic based resins, which can be either heat polymerized or auto polymerized (Choi et al, 2018). Other materials that are available for use as resilient liners include plasticized vinyl polymers, hydrophilic polymers, polyphosphazene, fluoropolymers, fluoroethylene (Anusavice et al, 2012).

Since acrylic-based liner resins have similar composition to the denture base resins they are expected to bond strongly without use of a primer or adhesive (Kreve et al, 2019). Silicone based reline materials have a different chemical composition to the denture base resins thus necessitate use of an adhesive to prevent frequent debonding (Choi et al, 2018).

Various mechanisms have been proposed to increase bond strength between soft denture relining material and denture base material including use of a primer, adhesive or monomer application; acid etching; application of organic solvents like acetone or isobutyl methacrylate solution, silica coating, application of Er:YAG laser and oxygen plasma treatment (Kreve et al, 2019, Atsu et al, 2013).

Various methods of testing mechanical properties of soft liners have been accepted in literature like tensile, shear and peel bond strength testing (Muddugangadhar et al, 2020). Peel testing of bond strength was first described by Kendall in 1971 and was used by Wright in 1982 to test adhesive strength of resilient liners. Peel testing had since been proposed to be the best method for testing of bond strength between reline material and denture base (Braden et al, 1995).

As previously discussed, it is to be expected that there will be an ever-increasing demand of patients seeking complete denture treatment. Removable prosthodontics will remain relevant in future. CECDs provide an attractive and increasingly popular alternative to conventional CRDPs due to their ease of fabrication, cost effectiveness and better physical properties. As a result of this it is also expected that more and more CRDPs will be fabricated by CAD/CAM technologies. Even with advent of implants, resilient liners with their multiple advantages and indications will keep on being needed and commonly utilized in removable prosthodontics.

Thus, it is my belief that testing of the bonding interactions of these materials is a relevant topic for prosthodontic researchers.

1.2 Literature review

1.2a Edentulism

Edentulism is defined as "the state of being without natural teeth" (GPT-9). It has also been rightfully described as "the ultimate marker of disease burden for oral health" (Cunha- Cruz et al, 2007). Although, edentulism is a highly prevalent oral condition worldwide (Emami et al, 2013), there is high variance amongst countries in prevalence of edentulism; with higher prevalence in developing world (Al-Rafee et al, 2020). Dental decay and periodontal disease, which are both bacterial biofilm mediated diseases, have been reported as the main causes of tooth loss (Cooper et al, 2018, Al-Rafee et al, 2020). However, there are multiple other factors than just biofilm mediated processes which are at play in relation to tooth loss. Old age, poor socio-economic conditions, female sex, have all been directly related to higher edentulous rates (Roberto et al, 2019). On the other hand, education levels and societal attitudes towards oral health are also considered equally important in increasing incidence of tooth loss and resultant subsequent edentulism (Al-Rafee et al, 2020)

Among geriatric population over 65 years of age, far greater number of edentulous persons is present, almost at a ratio of 2:1, when compared with dentate population (Lee et al, 2019). Peterson et al (2005) found edentulism to be highly associated with socioeconomic status. These findings by these two authors have been corroborated by Roberto et al (2019). In their systematic review, these authors also found demographic and socioeconomic factors to be most strongly associated factors with edentulism (Roberto et al, 2019).

There are still other factors which have also been associated with prevalence of edentulism. These causative factors for edentulism include but are not limited to poor access to oral health care, lack of third-party payer or insurance system, predisposing lower socio-economic strata (Lee et al, 2019). Farmer et al (2016) found in their analysis that cost or inability to pay was the most cited barrier in access to dental care. Chronic health conditions like rheumatoid arthritis, asthma, heart disease amongst others have also been associated with higher prevalence of edentulism as well

(Parker et al, 2020). Infact these authors found >50% higher prevalence of edentulism and severe tooth loss in adults over 50 years of age if chronic diseases were present (Parker et al, 2020).

Edentulism has serious deleterious effects on oral and overall systemic health of a patient. Edentulism directly impairs masticatory function leading to a patient preference for unhealthy processed diet due to difficulty in chewing and eating meats, fruits, vegetables (Parker et al, 2020). More importantly there is societal disability due to perceived deleterious esthetic consequences for edentulous patients (Emami et al, 2013). Thus, it has been concluded that edentulism affects overall quality of life for affected population due to compromised esthetics, speech, and function (Choi et al, 2020).

As a result, edentulous patients can be considered physically impaired, disable, and handicapped as per WHO criteria, mainly due to their inability to masticate foods properly and speech impediments. (Lee et al, 2019).

There have also been suggestions that edentulous individuals are at a greater risk of systemic diseases and increased mortality rate (Emami et al, 2013). This association between edentulism and systemic comorbidities has also been evaluated in depth by Felton et al (2016). In conclusion, importance of patient education to potential long-term harmful outcomes of tooth extraction needs to be emphasized (Felton et al, 2016).

Prevalence of edentulism was found to range from low of 11.25% to a high of 63.17% in a systematic review by Roberto et al (2019). WHO Global Oral Health Programme anticipated a 58% prevalence of edentulism in Canadians over 65yrs of age (Peterson et al, 2005). Millar and Locker in a 2005 Health Canada review, found total edentate population 65 years and older in Canada, had declined to 30% in 2003 from a high of 48% in 1990 (Millar et al, 2005).

There was also provincial variance noticed in numbers of edentate population in a Health Canada report. As per this report Quebec had highest prevalence of edentulous population at 14% while edentulous population in Manitoba was found to be at 7% (Miller at al, 2005).

Advent of preventative dentistry, better access to oral health care, more regular oral hygiene and checkups, access to fluoridated water, have contributed to reduction in prevalence in edentulism rates world over. (Cooper et al, 2019). There has also been higher public share of dental care along with an overall decrease in socio-economic inequality; these both have also contributed to reduction in overall edentulous rates (Millar et al, 2005). Felton et al (2011) found this relative reduction in United States to be approximately 78%. In-fact, in United States, there has been a trend for overall decline in prevalence of edentulism from 18.9% in 1957/58 to 4.9% in 2009/10. It is further expected, that edentulism in US will reduce to 2.6% by 2050 (Slade et al 2014). Comparable decline in edentulism that has been witnessed in Canada was less with edentulism rates of 23.1% in 1970's to 5.6% by 2009 (Farmer et al, 2016). In this comparative analysis of oral health inequalities between Canada and United States, it was indicated that even though prevalence of edentulism has overall declined in Canada in last 35years, this reduction has been slower compared to US due to persistence of oral health inequalities which could be linked to societal norms and economic conditions (Farmer et al, 2016).

As the world population increases, proportion of older individuals (60yrs and older) is growing faster than other age groups and is expected to double from approximately 600 million in 2005 to 1.2 billion by 2025 and more than triple to 2 billion in 2050 (Peterson et al, 2005). As edentulism is highly prevalent among older populations all over the world there is to be expected a corresponding increase in numbers of edentulous older people (Cooper et al, 2018, Peterson et al 2005, Roberto et al 2019).

Even with reduction in prevalence of edentulism, numbers of complete denture wearers were actually expected to increase to approximately 61million by 2020 in United States due to expected 79% growth in population (Douglass et al, 2002).

As a response to high prevalence of edentulism, L.F. Cooper's call to dentistry in 2018 "to reengage and redouble academic, clinical and scientific activities surrounding edentulism"; is prudent, timely and must be heeded. Similar importance must be acceded to L.F. Cooper's (2009) suggestion that "prevention of edentulism needs to be primary aspect of any broad-based contemporary strategy in global management of edentulism".

1.2b Residual ridge resorption

Residual ridge resorption or Reduction of Residual Ridges (RRR) is a major deleterious and inevitable consequence of tooth loss and long-term denture wearing (Pham et al, 2021). It is an insidious disease as resorption can eventually progress to the point of resorption of basal bone. Residual Ridge Resorption (RRR) has been described as an oral disease entity which presents as a chronic, progressive, irreversible, and cumulative condition (Atwood et al, 1971). In a follow up 25-year longitudinal study on residual ridge resorption in complete denture wearers, it was concluded that residual ridge resorption should be considered a serious prosthodontic problem (Tallgren et al, 2003).

Residual ridge resorption is characterized by loss of alveolar bone after loss of teeth and varies in rate, location, and amount from individual to individual and within same individual. (Atwood et al, 1971). RRR is considered multifactorial and thought to be a result of interaction amongst various factors - anatomic, metabolic, functional, and prosthetic (Atwood et al, 1971, Tallgren et al, 2003). Metabolic factors implicated in advanced bone resorption include systemic conditions like low calcium ingestion, advanced age, diabetes, osteoporosis, corticosteroid use and estrogen deficiency (Kubo et al, 2014).

In previously mentioned 25-year longitudinal study on residual ridge resorption, authors also found that rate of ridge resorption is most dramatic in first six months after extractions and then it slows down (Atwood et al, 1971). It is important to understand that residual ridge resorption continues through-out life (Atwood et al, 1971). In another study on morphologic changes after tooth extractions, authors concluded that in first year following tooth extraction, there was to be expected a 25% loss of bone width and approximately 4mm loss in bone height (Carlsson et al,1967). Resorption of residual alveolar ridges over a period of 7 years was shown to cause a pronounced reduction in morphologic facial height and an increased mandibular prognathism (Tallgren et al, 2003). Residual ridge resorption is much more pronounced in mandible as compared to maxilla; it is almost 4 times as compared to maxilla. That lead to conclusion that residual ridge resorption was a serious prosthodontic problem in mandibular edentate patients (Tallgren et al, 2003).

Also, one needs to understand that residual ridge resorption continues underneath complete removable dental prosthesis (CRDPs). In previously mentioned 25-year longitudinal study on residual ridge resorption in complete denture wearers, authors also found that reduction of residual ridges was rapid during first year of denture wear but slows down with protracted wear of dentures (Tallgren et al, 2003). In their another study from 1991, Tallgren et al, found a mean decrease of

5.7 mm in occlusal vertical dimension in approximately 2 years of immediate complete denture service (Tallgren et al,1991). In a review, various causative factors of alveolar ridge resorption underneath complete dentures were evaluated. Authors found that denture factors like occlusal form of teeth, incorrect occlusal relationship of denture teeth, deformation of denture base, loss of occlusal vertical dimension, continuous wear can be implicated as causative for residual ridge resorption (Kelsey et al, 1971). Patient gender, denture material and relining frequency have all been shown to have a significant effect on the rate of posterior residual ridge resorption (Pham et al, 2021).

This continuous residual ridge resorption leads to loss of adaptation of the CRDP after delivery (Kubo et al, 2014). It is expected that after a period of use, every CRDP will lose retention because of continuous residual ridge resorption (da Cruz et al, 2010). Residual ridge resorption will eventually lead to lack of stability and loss of retention, and it becomes even more pronounced in mandibular dentures (Bilhan et al, 2012). Loss of retention, irritation, impaired chewing ability will all eventually lead to decreased patient satisfaction with their CRPDs (Bilhan et al, 2012). Choi et al (2018) also pointed out that continuous ridge resorption is the leading cause of denture failure due to pain and discomfort. Ill-fitting CRDPs have also been linked to clinical findings like epulis fissuratum, inflammatory papillary hyperplasia, denture sore mouth or denture abused mucosa (Miller et al, 1977).

Endosseous implants, continuous service of CRDP’s through reline or rebase to maintain intimate contact with the denture base mucosa and to even consider timely replacement of CRDP are some of the suggested practices to manage residual ridge resorption (Cooper et al, 2009).

Residual alveolar ridge resorption is a continuous process that leads to unstable clinical conditions that will require a prudent practitioner to be aware of the process, monitor it continuously and plan accommodation of it in the prosthesis. (Cooper et al, 2009).

1.2c Complete removable dental prosthesis in management of edentulism

Edentulous state needs lifelong management and maintenance of prosthodontic therapy. This requires proper assessment of systemic health, oral, joint, and mucosal health, alveolar resorption, esthetic, and functional evaluations. (Cooper et al, 2018). One of the prosthetic therapies normally employed in management of complete edentulism is fabrication of a complete removable dental prosthesis (Choi et al, 2020).

Denture is defined as an “artificial substitute for missing natural teeth and adjacent tissues” (GPT-9). While a removable complete denture has been defined as “a removable prosthesis that replaces entire dentition and any associated anatomy of maxillae or mandible and can be readily inserted or removed from the mouth by the patient” (GPT-9).

Removable complete dental prostheses are frequently employed treatment modality for older patients in management of edentulism, even in industrialized countries (Peterson et al, 2005). Their popularity can be traced to advantages like ease of treatment appointments, they are economical and are a relatively easier to manage and maintain modality in treatment of edentulism (Bilhan et al, 2012). No wonder then, CRDP have been utilized for a long time in the treatment of edentulism world over (Emami et al, 2013). CRDPs can be expected to provide predictable long-term service as they have been shown to last longer than 15 years with proper maintenance procedures (Dorner et al, 2010). In a study reviewing patient satisfaction with CRDPs, authors concluded that overall patient satisfaction exceeded their expectations, especially when it came to denture esthetics (McCunniff et al, 2017).

In edentate patients, due to lack of teeth, there is a resultant decrease in patient’s chewing ability and capability. In a longitudinal study on chewing patterns in complete denture wearers it was discovered that when patients chewed on a residual anterior ridge, there was 3 to 4 times lower chewing activity than dentate patients (Tallgren et al, 1992). It would be expected that CRDPs will increase an edentate patient’s chewing ability and capability. However same longitudinal study; previously described; also showed that, chewing ability and chewing forces are still considerably lower in patients with CDRP as compared to dentate patients (Tallgren et al, 1992).

Since residual ridge resorption continues underneath complete removable dental prosthesis (CRDPs), Tallgren et al (1991) noticed gradual decrease in occlusal vertical dimension even with CRDP over 2-year study period. This reduction in vertical dimension even in a CRDP wearer due to residual ridge resorption was previously reported by Passamonti et al in 1981. Those authors noticed loss of vertical dimension of occlusion even at 3 months after insertion of immediate complete dentures (Passamonti et al,1981).

Empirically it was accepted that successful CRDP treatment depends upon the management of patient than on quality of the CRDP (Garrett et al, 1996). These authors reported in their study that masticatory performance and chewing efficiency did not improve with change from an ill-fitting denture (Garrett et al, 1996). This may be explained by the fact that it took up to year for an edentulous patient to show re-establishment of harmonious posterior occlusion with complete denture rehabilitation (Tallgren et al, 1989).

Even chewing strength takes about a year after denture insertion to be markedly improved in comparison to chewing strength a couple of weeks post denture insertion (Tallgren et al, 1992). This point was further emphasized in conclusion of a study evaluating effects of complete dentures on patient's masticatory ability. Authors of this study concluded that adaptation to complete removable prosthesis is a long-term process (Garrett et al, 1996).

Another important facet to our struggles with RRR, is to maintain an intimate relationship of the denture base to ever resorbing and changing residual ridge and mucosa. Barco et al, (1979) concluded by saying that accurate adaptation of denture base to the residual ridge will lead to a more stable CRDP and consequently higher patient satisfaction. Another study supported this conclusion and suggested that residual ridge resorption necessitated continuous replacement of the lost oral tissues, thus yearly evaluation for regular denture wearers is highly recommended (Tallgren et al, 2003). More recently, Einarsdottir et al (2020) have also stated that high quality CRDP's are associated with positive patient experience and continued usage.

Problems like lack of denture stability, retention, and comfort associated with an ill- fitting denture possibly as a consequence of residual ridge resorption, have led to an ever-increasing number of patients not utilizing any prosthesis after loss of all their teeth. It is estimated about 9% of Canadian edentulous patients were not wearing dentures (Millar et al, 2005). While reportedly, edentate population in United States that were not using dentures was estimated to be about 11% (Douglas et al, 2002).

To overcome some of these problems with CRDPs, Miller in 1958 reintroduced concept of overdentures (Miller et al, 1958). For the first time though, Ledger recommended in 1856 to dental professionals "to leave tooth stumps underneath a complete set of artificial teeth" (Ledger et al, 1856). Overdenture is defined as "any removable dental prosthesis that covers and rests on one or more remaining natural teeth, roots of natural teeth and/ or dental implants" (GPT-9).

Overdentures need constant care and maintenance and are associated with frequent fractures and loss of retention, but overall majority of overdenture wearers reported satisfaction with them (Ettinger et al, 1997). It is important to realize that posterior residual ridge resorption still occurs with overdenture and with time will lead to increased mobility of tooth supported overdenture base (Ettinger et al, 2019).

Implant overdenture can be a prudent treatment of first choice in patients who can not tolerate mandibular CRDP (Attard et al, 2004). Endosseous implants have also been described as a promising option in management of residual alveolar ridge resorption (Cooper et al, 2009). It is however important to note that a recent systematic review and meta-analysis showed that there is no significant difference in posterior residual ridge resorption between CRDP and 2 implant overdenture treatments (Pham et al, 2021). Though it has previously been shown that approximately 1.63 mm of posterior residual ridge resorption was seen in mandibles of complete denture wearers while in patients with implant supported overdenture wearer patient population in the study this resorption was 0.69 mm in 5 years (Kordatzis et al, 2003).

1.2d Denture base materials and manufacturing techniques

Denture base is defined as "the part of a denture that rests on the foundation tissues to which teeth are attached" (GPT-9). Denture base materials are defined as "any substance of which a denture base may be made of" (GPT-9).

Denture bases for CRDPs were made of ivory, gold, porcelain, vulcanite, aluminium, bakelite, celluloid, amongst other materials, till early twentieth century. Denture base materials can be broadly classified as metallic or non-metallic materials. Polymeric denture base materials can be classified based on ADA Specification No. 12 (figure 1) which includes type I, II and III denture base resins while ISO specifications have further added type IV (light-activated) and type V(microwave-cured) (Zafar et al, 2020). Denture bases may also be classified on basis of manufacturing methods, and these may include compression moulding, injection moulding, pour resin, additive manufacturing and subtractive manufacturing (Zafar et al, 2020).

i. Polymethyl methacrylate (PMMA)

Polymethyl methacrylate (PMMA) is the most often used non-metallic denture base material and will be discussed in more detail here.

Poly[1-(methoxy carbonyl)-1-methyl ethylene] is a synthetic polymer first reported in 1843 by Redtenbacher. PMMA was only introduced as a denture base material in powdered form in 1937 for denture base fabrication (Zafar et al, 2020).

PMMA for use as denture base is usually supplied as a powder-liquid system (Anusavice et al, 2012). Powder usually contains prepolymerized beads of PMMA with additives like pigments and fibers. Liquid consists of a monomer of methyl methacrylate along with cross linking agents and inhibitors (Zafar et al, 2020, Zarb et al, 2013, Anusavice et al, 2012). Composition of common denture base PMMA materials based on method of curing are listed in Table. 1 (Zarb et al 2013).

PMMA in powder liquid system, sets by a polymerization reaction which starts with mixing of both powder and liquid components. Activation of PMMA is achieved either chemically or through application of energy (heat, light, or microwave), by activation of an initiator which in turn leads to generation of free radicals. Once polymerization reaction is initiated it continues via binding of the monomers and will be terminated by chemical inhibitors added to the liquid (Zafar et al, 2020, Zarb et al, 2013).

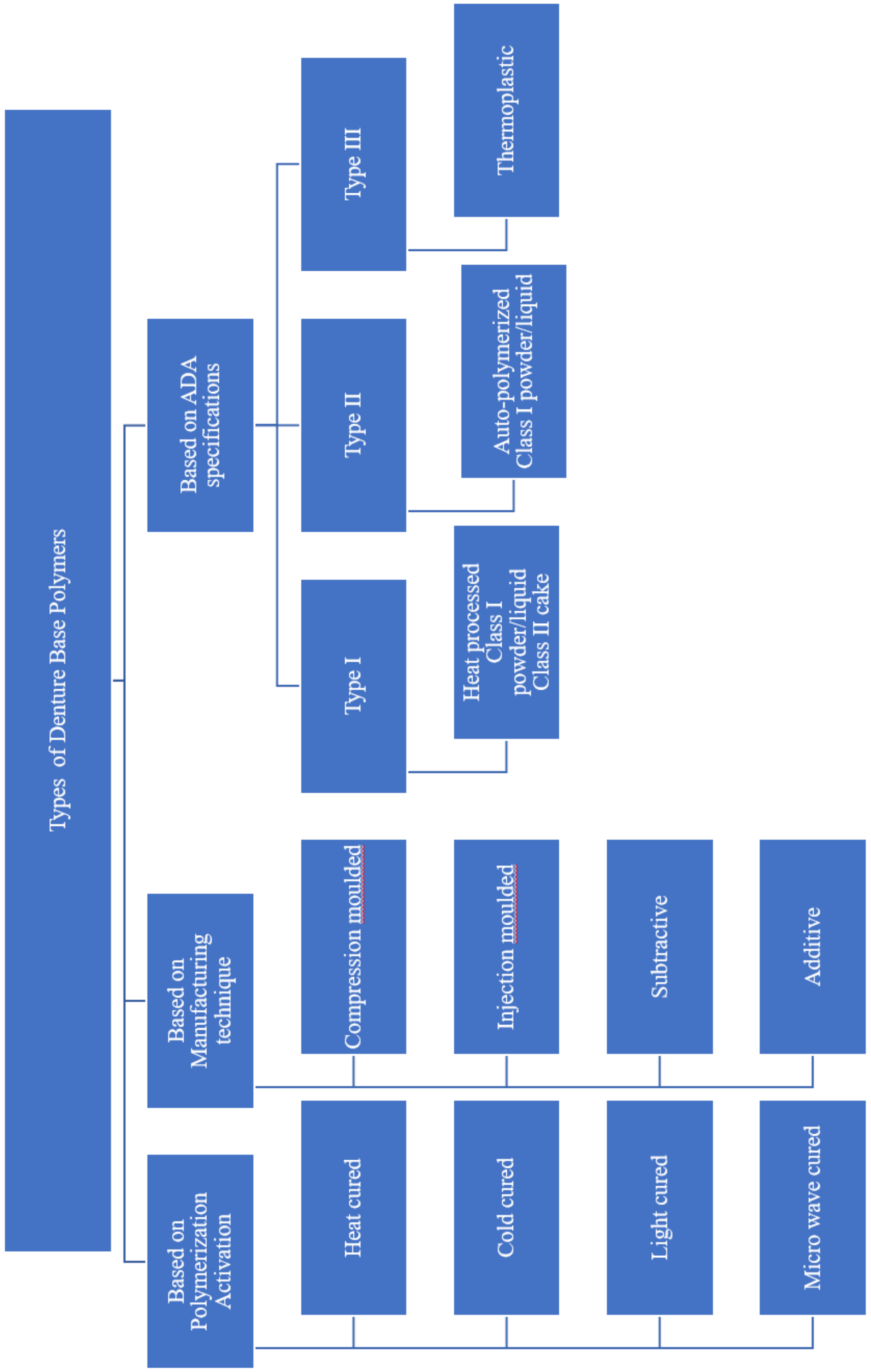
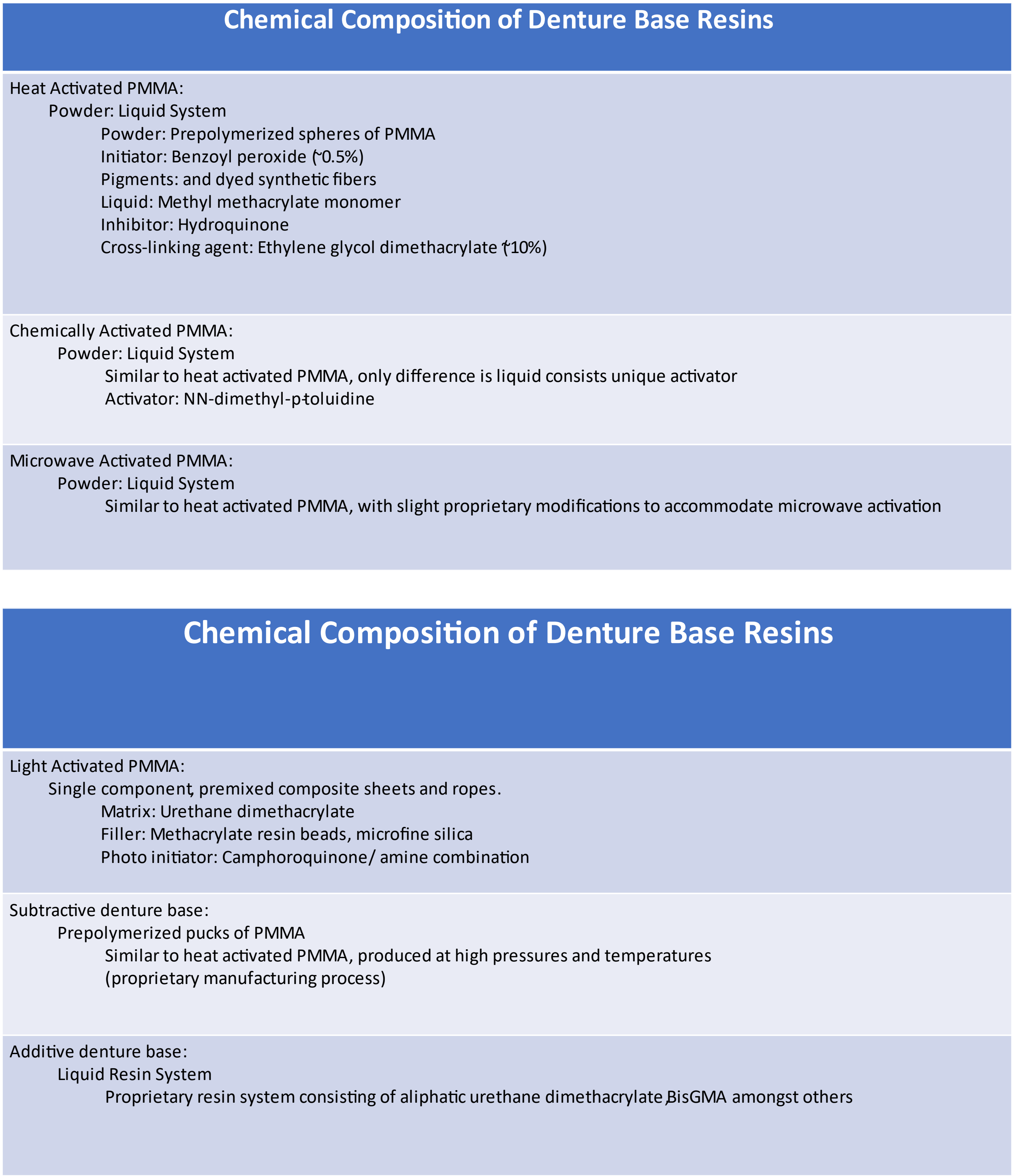


Figure 1. Classification of Denture Base Materials {Adopted from Zafar et al, 2020}



Chemical Composition of Denture Base Resins

Heat Activated PMMA:
- Powder: Liquid System
  - Powder: Prepolymerized spheres of PMMA
  - Initiator: Benzoyl peroxide (~0.5%)
  - Pigments: and dyed synthetic fibers
  - Liquid: Methyl methacrylate monomer
  - Inhibitor: Hydroquinone
  - Cross-linking agent: Ethylene glycol dimethacrylate (~10%)

Chemically Activated PMMA:
- Powder: Liquid System
  - Similar to heat activated PMMA, only difference is liquid consists unique activator
  - Activator: NN-dimethyl-p-toluidine

Microwave Activated PMMA:
- Powder: Liquid System
  - Similar to heat activated PMMA, with slight proprietary modifications to accommodate microwave activation

Chemical Composition of Denture Base Resins

Light Activated PMMA:
- Single component, premixed composite sheets and ropes.
  - Matrix: Urethane dimethacrylate
  - Filler: Methacrylate resin beads, microfine silica
  - Photo initiator: Camphoroquinone/ amine combination

Subtractive denture base:
- Prepolymerized pucks of PMMA
  - Similar to heat activated PMMA, produced at high pressures and temperatures (proprietary manufacturing process)

Additive denture base:
- Liquid Resin System
  - Proprietary resin system consisting of aliphatic urethane dimethacrylate, BisGMA amongst others

Table 1. Chemical composition of denture bases {Adapted from Zarb et al, 2013}

PMMA has many favourable properties like low density, esthetics, relatively low cytotoxicity, cost effective, easy to manipulate, and process, which lead to its increased use and popularity and by 1940’s it had replaced other denture base materials (Zafar et al, 2020).

On the other hand, PMMA has many deficiencies that prevent it from being an ideal denture base material. Disadvantages commonly associated with PMMA include complains that it absorbs water and is vulnerable to cyclic failure, has lower impact and flexural strength, is susceptible to microbial colonization, has high polymerization shrinkage and low wear resistance in human saliva (Anadioti et al, 2020, Zarb et al, 2013, Zafar et al, 2020).

To improve on these properties there has been continuous push for modification of PMMA. Various fibers like carbon, kevlar, polyethylene, etc. or fillers like alumina, zirconia, titania etc. have been employed with varying degrees of success to reinforce and modify PMMA (Zafar et al, 2020, Zarb et al, 2013, Anusavice et al, 2012). Similarly epoxy resins, polyamides or butadiene styrene have also been added to PMMA to improve the impact strength (Zarb et al, 2013, Zafar et al, 2020).

Alternately thermoplastic materials like acetal (AC) and polyamide (PA) have also been used as denture bases but they never received wide acceptance and popularity. Some authors have attributed this to their reduced modulus of elasticity thus imparting reduced chewing efficiency and lower occlusal forces (Macura- Karbownik et al, 2016).

a. Types of denture base PMMA

1. Heat-cured denture base PMMA

Heat cured PMMA for denture bases is usually packed in a doughy stage into brass flasks with lost wax technique utilizing a “compression- moulding technique” (Zarb et al, 2013). Alternatively an “injection moulding technique” was described by Pryor,W.J.(1942), that utilized specialized sprued flasks where fluid resin is injected under pressure while polymerization is occurring. It has since been popularized by Ivoclar Vivadent Inc. since 1970’s (Lee et al, 2019).

Benzoyl peroxide initiator is activated with heat energy and dissociates into carbon dioxide producing free radicals. Various heating/ curing cycles have been described in the literature.

Typically, a longer heating cycle will result in a higher degree of conversion with a decreased amount of residual monomer in cured prosthesis (Zafar et al, 2020). An appropriate curing cycle provides a high degree of polymerization thus imparting good physical properties to denture base. Residual porosity, polymerization shrinkage (about 7%), creation of residual stresses, and poor adaptation, still remain main concerns with heat cured denture base PMMA (Zafar et al, 2020).

Injection moulding has been shown to improve fit and adaptation of denture base (Zarb et al, 2013), reduce linear polymerization shrinkage to 0.65% and volumetric shrinkage to 1.09% (McLaughlin et al, 2019). This translates into better fit, accuracy, and dimensional stability of injection moulded denture base in comparison to conventional pack and cure techniques (Lee et al, 2019, Zarb et al, 2013). Additional benefits are that injection moulding equipment can be utilized to process other denture base materials like polycarbonates, nylon, and polyvinyl acrylics (Zarb et al, 2013).

Conventional "flask and press" techniques of CRDP have been now well established for over half a century and haven't changed much (Srinivasan et al, 2018). Readers are also reminded that the clinical predictability of conventional CRDP manufacturing techniques has been established successfully over almost a century (Bidra et al, 2013).

Conventional clinical methods of complete removable denture fabrication have also been established for over 80 years and generally involve five steps from fabrication to delivery (Wimmer et al, 2016). Some of the often-enlisted disadvantages of traditional clinical technique of CRDP manufacture have been increased number of treatment and post insertion adjustment visits, higher costs due to increased chair time, varying fit due to polymerization shrinkage. (Bidra et al, 2013)

2. Cold-cured denture base PMMA

These denture base materials are also known as chemically cured or auto-polymerizing PMMA. They are distinct from heat cured PMMA as autopolymerized PMMA do not need heat energy for free radical creation. Autopolymerized PMMA have a tertiary amine activator like NN- dimethyl-p- toluidine instead to start the reaction. Tertiary amine activator in the liquid once in contact with benzoyl peroxide initiator in the powder will lead to free radical formation and allow polymerization to occur. (Zarb et al, 2013)

Cold cured PMMA can be used in doughy stage and packed similarly to heat cured PMMA in brass flasks but more commonly they are employed through "pour or fluid resin technique" (Zarb et al, 2013).

Since degree of polymerization is lower with chemical cured PMMA, in comparison to heat cured resins, properties of auto polymerized PMMA are generally inferior. (Zarb et al, 2013). Auto-polymerizing resins generally have higher monomer content at ≈3 % to 5%, decreased conversion, increased creep rates, higher solubility, inferior colour stability and suffer from overall inferior mechanical properties compared to heat cured PMMA (Zarb et al, 2013). Interestingly, since these materials have reduced residual stresses during polymerization, they are more dimensionally stable than their heat cured counterparts (Zarb et al, 2013).

The drawbacks of autopolymerized denture base PMMA have been such that their use has been limited to provisional dentures, for duplicating existing dentures and for denture repairs only (Zafar et al, 2020).

3. **Microwave-cured denture base PMMA**

Microwave cured denture base PMMA material does not have a benzoyl peroxide initiator and instead this procedure utilizes microwave energy for free radical creation and polymerization (Zarb et al, 2013). Microwave curing for fabrication of denture base fabrication technique became popular in 1983 with introduction of metal free flasks. This fabrication technique has a practical benefit of short curing times for a denture base that is comparable to heat cured resins in mechanical properties, for most part. They also claim greater dimensional stability and less tooth movements during curing (Zarb et al, 2013, Zafar et al, 2020). Biggest drawbacks have been described as cost effectiveness and claimed issues with bond strength of acrylic denture teeth to the microwave cured denture base; thus, limiting their more widespread use (Zafar et al, 2020).

4. **Light-cured denture base PMMA**

Light cured denture base PMMA materials work on principles similar to resin-based light cured composites and are cured when the champhoroquinone photo initiator is exposed to visible light (Zafar et al, 2020). Their purported biggest advantage is lack of methyl methacrylate monomer and thus light cured denture bases can be used in patients sensitive to methyl methacrylate

(Gohlke-Wehrße et al, 2012, Zarb et al, 2013). Light curing also allows easier and better control during material manipulation due to increased control over curing cycle (Zafar et al, 2020). As an added benefit light cured denture base materials also exhibit less polymerization shrinkage than heat cured denture base resins (Gohlke-Wehrße et al, 2012). Light cured denture base materials however have generally inferior properties as compared to heat cured PMMA and thus have fallen out of favour as a denture base material (Zarb et al, 2013, Anusavice et al, 2012).

b. Properties of traditional denture base PMMA

PMMA has been shown to have acceptable biocompatibility (Zafar et al, 2020), but there are reactions to denture base PMMA which have been described as both allergic and local chemical irritation (Weaver et al, 1980). All denture base acrylics have some cytotoxicity, but heat polymerized acrylic denture resins processed in a water bath are thought to have least cytotoxicity (Chaves et al, 2012). Most of the reported cytotoxicity is due to leaching of unreacted residual monomer, other constituents, and reaction by-products, released during use (Rashid et al, 2015). It has been recommended that once processed, PMMA based denture bases should be stored in water for 24 hours before delivery to elute and reduce amount of residual monomer content. Thus, potentially eventually reducing cytotoxicity of the acrylic denture bases (Zafar et al, 2020).

There are multiple complex processes intra-orally that lead to biodegradation of denture base resins, release of potentially toxic compounds and eventually detrimentally effect physical and mechanical properties (Bettencourt et al, 2010). Cytotoxic effect of denture base PMMA resins can also be increased due to daily immersion in some of the commonly used disinfectants. As such caution has been recommended in choosing proper disinfectant for the selected denture base material being used (Masetti et al, 2018).

Denture base PMMA resins have acceptable mechanical and physical properties with good flexural strength, acceptable tensile and compressive strength, and good fracture toughness. Though some of the drawbacks include low colour stability, poor thermal conductivity, impact strength is very low. There have been attempts to improve some of these properties by inclusion of additives like butadiene styrene (Zafar et al, 2020).

Poor oral hygiene, poor denture quality and nocturnal use of dentures may lead to fungal infestation of the CRDP (Yarborough et al, 2016). Candida adherence to the denture base is dependent on the formation of dental plaque on the denture surface. This is thought to be directly related to surface free energy and surface roughness of the denture base (Pereira-Cenci et al, 2008). Quirynen et al (1990) postulated there is a critical threshold of 0.2µm for surface roughness beyond which microbial adhesion will occur. If denture base is highly polished so that surface roughness is less than 0.2µm, it will interfere with biofilm adhesion (Pereira-Cenci et al, 2008).

Stringent oral hygiene along with possible surface modifications to change the surface charge have been recommended to resist microbial aggregation (Zarb et al, 2013). In a seminal work on denture care and maintenance, importance of at home oral and denture hygiene is emphasized and authors recommended various strategies to reduce microbial burden on dentures (Felton et al, 2011). A group of authors systematically reviewed nanoparticle modified PMMA for anti-fungal effectiveness. These authors concluded silver and zinc oxide nano particles show promise but much more research is still needed in this aspect before clinical application will be viable (Garcia et al, 2021).

ii. Computer Engineered Complete Denture CECD

Glossary of prosthodontic terms have defined “digital denture as a complete denture that is created by or through automation, incorporating use of computer aided design (CAD), computer aided manufacturing (CAM) and computer aided engineering (CAE)” (GPT-9, Baba et al, 2021).

CAD-CAM denture manufacturing can either involve a digital design process or may involve only a digital fabrication processes or may utilize both digital design and manufacturing processes. Even the process of computer aided manufacturing (CAM) itself could be subtractive or additive. Thus, to reduce confusion around digital dentures; Kattadiyil et al (2017) coined this term computer engineered complete denture (CECD); to describe all complete dentures that are manufactured using computer aided design (CAD) and computer aided manufacture (CAM) processes. These authors recommended use of computer engineered complete dentures (CECD) as an encompassing term to provide consistency and uniformity to the digital fabrication process of complete dentures (Kattadiyil et al, 2017).

Current revolution in digital manufacture of dentures started in 1994 with publication of first report by Maeda et al; describing use of laser scanning and laser lithography (rapid prototyping) to assist in fabrication process of a complete denture. Then in 1997, Kawahata et al reported use of laser scanners and CNC machining to duplicate an existing complete denture thus introducing milling process in denture manufacture. Proof of successful patient treatment with a milled CECD was finally provided by Goodacre et al in 2012. This group of authors described their clinical process and delivered a patient with a clear plastic complete removable denture subtractively manufactured using 3 axis milling. Since then, use of CAD-CAM complete dentures or digital dentures have exploded in popularity.

A quick search by this author on PUBMED with only CAD-CAM dentures as inclusion criteria produced numerous articles on this topic in just last couple of years, showing ever increasing interest and ongoing research in digital dentures. Srinivasan et al (2018) reasoned that popularity of CECD is partly in response to changing attitudes and trends for innovation among clinicians and dental technicians. A google search by this author for denture service providers and their respective websites in local area show most providers marketing digital dentures as a new, enhanced and overall, a better patient service.

Conventional methods of complete denture fabrication are beset with some problems which were included in a systematic review on computer aided technology in complete dentures (Bidra et al, 2013). These drawbacks have traditionally included, but are not limited, to minimum 4-5 clinical steps requiring patient visits followed by multiple post-insertion adjustment appointments. Increased patient visits translate into increased clinical costs for both provider and the patient. Polymerization shrinkage which may affect the intimate fit of denture base to underlying tissues, among others has also been described as another major issue with conventional methods of compression moulding complete dentures (Bidra et al, 2013). Same group of authors of this previously described systematic review, also contend that these disadvantages associated with conventional complete dentures are significant enough to warrant dentists in United States decline offering this excellent treatment modality to their patients (Bidra et al, 2013).

This inference of Bidra et al (2013), on disadvantages of conventional manufactured CRDPs was also supported by Anadioti et al in 2020 through their narrative review. This group also mentioned susceptibility to microbial colonization, lack of radio-opacity, monomer leaching, degradation of mechanical properties and low wear resistance in saliva as other potential disadvantages of conventionally processed acrylic denture bases (Anadioti et al, 2020).

In comparison to conventionally processed CRDP’s, Bidra et al (2013), enlisted some indications and advantages for CECDs as well through their systematic review. Authors suggested that a growing edentulous population in US that is demanding more complete denture prosthesis, possibly easier implementation for CECD in public health programs and shortage of skilled dentists and laboratory technicians providing quality conventional denture care are some of the clear indications of CECD (Bidra et al, 2013). Maragliano-Muniz et al (2021) made an effort to provide some clarity to clinicians wanting to incorporate digital dentures into their clinical practice. These authors mentioned that some of the indications for CECD’s could be any patient requiring maxillary and mandibular CRDP, denture duplication, immediate CRDP, bar supported overdentures or when a mandibular two implant assisted overdenture was going to be manufactured (Maragliano-Muniz et al, 2021).

Most of the methods employed in fabrication of CECDs have some common elements and have been reported to include digitisation of patient records to digitally design the prosthesis, this is then followed by either a CNC milling process or a 3-d printing process (Kattadiyil et al, 2017, Wimmer et al, 2016). Methods of fabrication have also been described as semi-digital or fully digital based on different workflows and can potentially be accomplished in as little as 2 appointments (Schweigera et al, 2018).

More commonly employed subtractive technique for CECD manufacturing can be described as a milling process (Maragliano-Muniz et al, 2021). A subtractive digital denture is milled from either a single monolithic prepolymerized PMMA puck which has both denture base and denture teeth included into it. Or, by milling of separate prepolymerized denture base and tooth pucks, which then will be bonded together afterwards for a two-piece prosthesis (Maragliano-Muniz et al, 2021).

Srinivasan et al (2018), described additive manufacturing process as a serial appositional process whereby a denture resin material is accumulatively layered and cured to create a CECD. UV light, visible light, lasers have all been employed in this curing process (Srinivasan et al, 2018).

Even though digital manufacturing techniques have automized the production of the denture base and teeth, it is important to note though that, digital fabrication process still needs a technician. A good technician with dental background is required to design a CECD using CAD software, manually bond teeth onto denture base in case of 2 piece milled prosthesis and for all the printed dentures, manually finish and polish the cameo surface of the prosthesis (Steinmassl et al, 2017).

Baba et al in 2021 provided a literature review on CAD/CAM complete denture systems available in the market and their physical properties. One of the standouts of this paper was that subtractive manufacturing through use of milled CECD is much more mainstream and popular as compared to additive manufacturing. Authors included reports in their literature review that suggested use of 3D printing for fabrication of trial dentures only with final prosthesis being manufactured eventually either through milling or conventional processing. (Baba et al 2021). A case in point is Avadent digital dentures system. In this very popular CECD system, final prosthesis is manufactured with subtractive process while rapid prototyping use is limited to trial dentures only (Schweigra et al, 2018, Baba et al, 2021).

Additive manufacturing as compared to subtractive fabrication, offers unlimited geometry options, reproduction of finer details, faster speed, greater ability to mass production and much lower material waste thus being more economical and environmentally more favourable process (Wang et al, 2021). It is still limited to trial denture fabrication. A proof-of-concept case report from 2018 on in-office 3d printed immediate denture, mentioned that all the additively manufactured denture resin materials available in US at that time were approved for interim use only (Lin et al, 2018).

Jurado et al (2019) enlisted excellent fit and less expensive production equipment as benefits of printed dentures. They also suggested that even though subtractive manufacturing is much more common, additive techniques are only recently starting to develop and not indicated yet for permanent use (Jurado et al, 2019). In a systematic review on clinical complications and quality assessments with CECDs, it was mentioned that additive manufactured CECD suffer from lack of long term dimensional and colour stability and may have strength issues (Kattadiyil et al, 2017). In another review on 3d printed complete dentures, authors also commented upon additive manufactured CECD having less dimensional stability over time as compared to milled CECD and relatively lower flexural strength (Anadioti et al, 2020). Questions have also been raised about polymerization shrinkage associated with post curing process of printed dentures and potential for skin sensitization due to unpolymerized denture resins (Jurado et al, 2019). In a previously mentioned narrative review on 3D printed CRDP as well, authors suggested that additively manufactured complete dentures at this time, are mainly being used for trial dentures and immediate dentures (Anadioti et al, 2020). Authors explain this based on poor esthetics and retention of printed dentures and lack of long-term studies (Anadioti et al, 2020).

ii(a). Advantages of CECD

Most of the authors agree on advantages of CECD’s which among others include less chair time, better mechanical properties, increased biocompatibility, and better fit in comparison to conventional CRDP’s (Jurado et al, 2019). Kattadiyil et al (2017) described three most significant advantages of CECD as compared to conventional CRDP being a reduced number of appointments required, improved prosthesis fit and retention and option of electronic archiving the case.

i. Accuracy and fit of CECD

It was shown a long time ago that accuracy of the denture base is very important as accurate denture bases have better adaptation to the underlying tissues. It has been concluded that intimate fit to underlying tissues results in production of an overall much more stable prosthesis (Barco et al, 1979).

In a comparison between fit of conventionally fabricated maxillary CRDP with that of a milled maxillary CECD; authors concluded that milled dentures showed significantly better adaptation to the shallow palate models as compared to conventional compression moulded dentures (McLaughlin et al, 2019). Interestingly in the same comparative study, injection moulding process of conventional denture manufacture performed similar to the milled dentures (McLaughlin et al, 2019). This result disagrees with Goodacre et al (2016) study though, which compared denture base adaptation of milled dentures with compression moulding, fluid resin pour and injection moulding techniques. This group of authors concluded that CAD/CAM fabrication process was most accurate and reproducible complete denture fabrication technique when compared with more popular conventional denture fabrication techniques. (Goodacre et al, 2016). This difference may be explained by the different types of palatal and ridge configurations tested in both studies. Goodacre et al (2016) study used ACP Class I ridge and palatal morphology for comparison while McLaughlin et al (2019) study used various palatal depths and configurations varying between ACP Class I and IV including shallow palates. As we now know, adaptation of a milled dentures can also be affected by size of milling bur, characteristics of area to be milled and machining axis (Lee et al 2019).

Injection moulding method was also shown to be significantly lower in accuracy of fit as compared to digital manufacturing in another study comparing injection moulding with additive and subtractive denture bases (Lee et al, 2019). More interesting was the fact that injection moulding in this study was shown to have higher resolution than both subtractive and printed denture base manufacturing (Lee et al, 2019). More recently, a systematic review of in-vitro studies on accuracy of CECDs concluded that digital complete dentures show similar or better denture base adaptation to the underlying denture base tissues (Wang et al, 2021). Similarly, both additive and subtractive manufacturing has been suggested to have higher trueness for intaglio surface than conventionally fabricated dentures (Kalberer et al, 2019). This has previously been commented upon as well by Srinivasan et al (2018). These latter authors mentioned that trueness of CAD/CAM CRDP's is clinically acceptable and is non-inferior to conventional manufactured CRDP's (Srinivasan et al, 2018).

ii. Retention of CECD

Denture retention is defined as the "resistance in movement of denture away from its tissue foundation in a vertical direction" (GPT-9).

Better adaptation of a denture base to underlying tissues has been described as the singularly most important factor in denture retention (Darvell et al 2000). Thus, it stands to reason that a more accurate prosthesis with intimate fit should have good retention. Denture fabrication quality was enlisted as one of the important factors affecting quality of fit of a denture which was deemed central to treatment success (Darvell et al 2000).

Enhanced retention of CECD has been one of their most valued advantages over conventional CRDPs (Kattadiyil et al, 2015, Bidra et al, 2016, Kattadiyil et al, 2017). Enhancement in retention with CECD was proven in a clinical study comparing effects of denture adhesive on the retention of milled and heat-activated maxillary denture bases (AlRumaih et al, 2018). Here also milled denture bases performed much better in retention measurements than conventional complete dentures both with and without a denture adhesive (AlRumaih et al, 2018). Efforts were made to measured enhanced retention in CECDs using force gauges as well. In a study using a mechanised vertical pull out force test, increase in retention force was found to be of the magnitude of 19.9 N in maxillary milled complete denture as compared to conventional heat processed denture base (Al Helal et al, 2017). This increase was significant enough that these authors recommended milled denture bases in cases where enhanced retention of complete dentures was indicated (Al Helal et al, 2017).

CECD fabrication process eliminates traditional PMMA polymerization processes required during conventional methods of CRDP fabrication. Infact, elimination of polymerization process and associated shrinkage had been described as the single biggest achievement of CECDs (McLaughlin et al, 2015). As subtractive manufacturing utilizes prepolymerized pucks and additive manufacturing process uses resins with negligible amounts of monomer, there is no polymerization shrinkage with CECD, that is so often associated with traditional PMMA and seen in conventional manufacturing processes (Jurado et al, 2019, Lee et al, 2019). This reduction in polymerization shrinkage associated with PMMA has also contributed significantly to enhanced fit and retention of CECD in comparison to conventional CRDP (McLaughlin et al, 2019, Kalberer et al, 2019).

iii. Reduced adherence of Candida albicans

Zafar et al (2020) in their review on PMMA use in dentistry, concluded that candida albicans showed reduced adherence to both subtractively and additively manufactured dentures. Bilgin et al (2016) reviewed CAD/CAM techniques for CECD fabrication. These authors were probably the one of the first to suggest that there was a decreased risk of micro-organism colonization and consequent infections with CECDs (Bilgin et al, 2016). Another group systematically reviewed the clinical outcomes of CECD in 2017. They questioned claim of reduced microbial adhesion by Bilgin et al (2016) though as those authors didn’t provide a supporting study in favour of this claim (Kattadiyil et al, 2017). Since then, multiple other authors have concluded that CECDs do; indeed, show reduced microbial adherence (Anadioti et al, 2020, Baba et al, 2021, Maragliano-Muniz et al, 2021). Reduced microbial adhesion can be explained basically due to a few factors. It has been mentioned that CECD are more hygienic as a result of a reduced surface roughness (Ra value) and a higher contact angle making them more hydrophobic (Arslan et al, 2018). This reduced roughness and increased hydrophobicity for CAD/ CAM dentures has been supported in an update on prosthodontic applications of PMMA and thought to lead to reduced microbial adhesion (Zafar et al, 2020). But Baba et al (2021) refuted this mechanism of microbial adhesion. They concluded that CAD/CAM PMMA is more hydrophilic than conventional manufactured acrylic denture bases. But they still accepted reduced adherence potential of candida albicans to CECD. Among their included supporting studies one of the conclusions was that most CAD/CAM dentures attracted less microbial colonization because of smoother surface and increased hydrophilicity (Steinmassl et al 2018). Baba et al (2021) also quoted Al Fouzan et al (2017) study, amongst others, in support for their conclusion on reduced microbial adhesion due to hydrophilicity (Baba et al, 2021). Al Fouzan et al (2017) attributed reduction in microbial adherence to the decreased surface roughness and to reduced porosities of CAD/CAM dentures. They did not directly attribute reduced adhesion to increased hydrophilicity of CAD/CAM PMMA (Al Fouzan et al, 2017). Reduced porosities in CAD/CAM PMMA are supposed to be a result of longer polymer chains and higher degree of conversion (Baba et al, 2021). CAD/CAM PMMA having less porosities in comparison to conventional heat cured denture base PMMA is also supported by Bidra et al (2013) and Maragliano-Muniz et al (2021). Authors in latter study mentioned that prepolymerized CAD/CAM pucks are much more homogenous with no porosities. This homogenous nature with less porosities of prepolymerized PMMA pucks used in additive manufacturing of CECD, is what allows them to resist fungal and microbial infiltration and adherence (Maragliano-Muniz et al, (2021).

iv. Mechanical properties in CECD

Srinivasan et al (2018) reported that even though CAD/CAM PMMA are similar to conventional PMMA in chemistry, CAD/CAM PMMA have enhanced properties due to proprietary manufacturing processes. These processes allow a higher degree of conversion with extremely low residual monomer and much more homogenous pucks to be achieved due to utilization of high pressure and temperatures; thus, imparting enhanced mechanical properties to CAD/CAM PMMA (Maragliano-Muniz et al, 2021).

CAD/CAM PMMA has increased hardness, durability, flexural modulus and impact strength (Zafar et al, 2020). These properties result in lower fracture rates of 2.08% in CECD’s as compared to 5.8% fracture rates found in conventional CRDP’s (Kattadiyil et al, 2017). CAD/CAM PMMA are also shown to have improved flexural strength (Zafar et al, 2020) thus allowing CECDs to be milled to reduced thickness of up to 1.5mm (Alaseef et al, 2022). In the same study authors concluded that additive manufactured denture bases could only be printed to a thickness of 2mm for clinically acceptable flexural properties (Alaseef et al, 2022). Conventional PMMA is shown to have lower flexural strength as compared to CAD/CAM prepolymerized PMMA employed in milled digital dentures (Arslan et al, 2018). Thus, CECDs can be generally milled to thinner uniform base with higher strength allowing increased patient comfort and acceptance of prosthesis (Baba et al, 2021).

In addition to this subtractive manufactured CECDs have been shown to be more dimensionally stable and exhibit less deformation than both compression and injection moulded conventional CRDPs (McLaughlin et al, 2019).

v. Monomer leaching in CECD

Conventional PMMA sets by reaction initiated by mixing of polymer powder with liquid monomer. There is always some amount of undissolved polymer and unreacted residual monomer left as the polymerization progresses. Some of this residual monomer is evaporated and some is further removed because of heat application during polymerization reaction which also leads to higher degrees of polymerization reactions (Zafar et al, 2020).

However, a certain amount of residual monomer is always left behind even though it will be desirable to achieve zero residual monomer at termination of polymerization reaction. This has been explained due to monomer- polymer equilibrium necessary for free radical mediated polymerization reaction employed by denture base resins (Steinmassl et al, 2017). Unreacted monomer leaches out of a denture base acrylic resin by process of diffusion and may be responsible for their cytotoxic effects (Rashid et al, 2015). Thus, this residual monomer can lead to both local chemical irritation and allergic reactions to acrylic resins (Weaver et al, 1980).

As subtractively manufactured CECD utilize pre-polymerized pucks it can be hypothesized that we may not have as much residual monomer content with CECD’s (Arslan et al, 2018). Additive manufacturing on the other hand utilizes monomers based on acrylic esters again leading to much lower residual monomer content (Alaseef et al, 2022).

CECDs actually do release very little monomer (Arslan et al, 2018). An evaluation of Baltic denture system (Merz Dental GmbH, Lütjenburg, Germany), Vita vionic (Bad Säckingen, Germany), Weiland digital dentures (Wieland Dental + Technik GmbH&Co. KG, Pforzheim, Germany/Ivoclar Vivadent AG, Schaan, Liechtenstein) and Whole you Nexteeth system (Whole You Inc., San Jose, USA) showed that CAD/CAM fabricated dentures do not necessarily release significantly less monomer than compression moulded, and heat processed conventional CRDP (Steinmassl et al, 2017).

vi. Reduced number of appointments with CECD

As previously mentioned CECD's can be manufactured in a simplified manner over much fewer appointments (Bilgin et al, 2016, Janeva et al, 2018). They may be manufactured in as few as 2 visits for Baltic denture system, but most popular CECD systems are utilizing 3 or 5 visits like Avadent digital dentures, Ivoclar digital dentures (Schweigera et al, 2018). It seems though, with an experienced clinician familiar with CECD system, most of the CECD manufacturing systems can give predictable results on average in 3 visits (Baba et al, 2021). Similarly, number of post insertion adjustment appointments is markedly reduced with CECD. Patients treated with CECD were shown in one study to require on average only 2.08 post placement adjustment visits over 1 year (Kattadiyil et al , 2017); while in another it was an average of 3.3 post insertion denture adjustments (Bidra et al, 2016).

As a result, the reduced clinical chair time required will benefit the clinical provider, but it may also be preferred by the patients (Al Helal et al, 2017).

vii. Patient acceptance of CECD

Kattadiyil et al (2015) were arguably first in reporting patient centered outcomes for CECD. Significantly higher average patient outcome scores were reported through patient responses and faculty evaluation. Even the undergraduate students who were providing the treatments in this study preferred digital complete dentures over conventional fabrication processes. As an added benefit it was reported that CECDs in this study had increased retention (Kattadiyil et al, 2015). In another prospective study evaluating patient centric outcomes revealed 80% patient satisfaction with CECDs. The biggest advantage associated with CECDs in this study was statistically significant improvement seen in patient ratings regarding lack of sore spots (Bidra et al, 2016).

viii. Digital data archiving of CECD

It has been suggested that easy reproducibility (creation of duplicate dentures) is an added benefit only afforded by the stored digital data in case of CECD (Bidra et al, 2013). This sored digital data or digital archiving has been described as “the ability to provide a replacement or spare prosthesis using stored digital data” (Al Helal et al, 2017). Ability to digitally archive is possibly the biggest advantage of CECD as this allows an easy and quick recall and automated refabrication if needed (Janeva et al, 2018).

iii(b) Disadvantages of CECD

Most cited problem with CECDs has been high material costs for CECD protocols (Srinivasan et al, 2019). Initial set up cost for the digital manufacturing systems can be exorbitant and prohibitive for some providers (Jurado et al, 2019). Moreover, subtractive manufacturing process of milling is wasteful, and resins used for additive manufacturing produces can be toxic and need careful handling. While the by products of both these CECD manufacturing processes are environmentally harmful and thus difficult to dispose (Baba et al, 2021). Another possible barrier in implementation of digital dentures in practice could be the steep learning curve associated with mastering the new techniques and technologies. This may be overwhelming in the beginning and possibly an insurmountable barrier to digital dentures for some (Jurado et al, 2019).

Most of the digital systems employ conventional impression taking and other steps of maxillomandibular relationship recording and transfer, which can be time consuming to ship and may distort during shipping thus causing manufacturing challenges (Bilgin et al, 2016).

Another big potential problem with digital denture systems, which is the inability for some to evaluate virtual esthetics reliably (Anadioti et al, 2020). Same problem was reported by predoctoral students when using digital dentures in an institution based study (Kattadiyil et al, 2015). Virtual tooth set up also limits opportunity for patient input in their own treatment as well and may affect their acceptance of final prosthesis (Bidra et al, 2013). To overcome this a virtual wax try in through a fully digital approach using facial scans integrated with intraoral scans and virtual teeth setup has been recommended (Schweigera et al, 2018). This difficulty in esthetic evaluation was previously compounded by lack of a trial denture appointment with expediated digital denture systems. Thus, limiting providers ability to esthetically evaluate the prosthesis before final fabrication of the CECD which in most cases will be an expensive proposition to replace (Anadioti et al, 2020). Since then, most of the common and popular digital denture systems now provide the ability for practitioner to order a printed trail denture to evaluate esthetics, function, and phonetics (Baba et al, 2021).

This problem was also creatively solved previously by McLaughlin et al (2013). These authors described an excellent method of utilizing milled denture bases with a wax trial placement for complete control over esthetic. This would then be followed by conventional processing techniques over the same milled base (McLaughlin et al, 2013). There may be concerns about double processing and its effect on dimensional stability of denture bases due to residual stress relaxation during second processing step (Einarsdottir et al, 2020). This approach of second processing has also been supported by the same group of authors whose study looked into dimensional stability of double processed complete denture bases manufactured by milling, compression moulding, and injection moulding. They found that second processing had negligible clinical effects on dimensional stability of mandibular denture regardless of which denture base processing technique (Einarsdottir et al, 2020).

There is still an issue for dentists and prosthodontists who want to utilize balanced occlusion for their patients needing CRDPs. We still can not digitally plan a CECD in balanced occlusion (Anadioti et al 2021). As of now, this can only be rectified using a clinical remount procedure necessitating an additional clinical step (Baba et al, 2021).

Most of the studies on the higher retention of milled CECD are short term and we lack long term data (Kattadiyil et al, 2017). In addition to this it is still unclear if milled CECDs offer increased retention in mandible as well as maxilla (Al Helal et al, 2017). There also seems to be an issue with additively printed CECD; in that they do not seem to have same retention as milled dentures thus often requiring reline for clinical acceptability (Anadioti et al, 2020). This need for immediate relines has been also concluded to be one of the problems with CECDs in another systematic review (Kattadiyil et al, 2017). In their systematic review of complications with CECD, patient dissatisfaction with the prosthesis (25.49%) and lack of retention (20.73%) were 2 highest percentage complications with CECDs (Kattadiyil et al, 2017). To overcome these and esthetic discrepancies, authors strongly recommended use of a trial denture (Kattadiyil et al, 2017).

Since there are ever newer CAD/CAM denture base resins and digital protocols of CECD manufacturing coming up, it remains to be seen if all these CAD/CAM materials can be reliably relined (Srinivasan et al, 2018). Attention to trial printed dentures in regard to stability and esthetics have also been drawn based on a study using both patient and prosthodontist ratings (Inokoshi et al, 2012).

In presence of deep undercuts milling may not produce most intimate prosthesis due to inherent limitations of CNC machining process (Lee et al, 2019). In such cases rapid prototyping may provide more intimate fitting prosthesis but as of now we are still lacking long term studies on printed dentures and as such they are not indicated for long term use (Anadioti et al, 2020). In such situations a reline procedure of a CECD or a conventional CRDP manufacturing method may still need to be employed. It was recommended that even in cases with a shallow ovoid palate, injection moulding may be the technique that should be employed for manufacturing CRDP (McLaughlin et al 2019).

Even with all these potential limitations to CECDs, overall patient satisfaction with CECDs remain high due to fewer appointments and provider acceptance has been encouraging as well due to greater accuracy with simpler techniques (Maragliano-Muniz et al, 2021). Thus, the ever-expanding digital complete denture market.

Some of the available and more popular CECD systems in the market right now include Avadent digital dentures (Global Dental Science LLC, Scottsdale, AZ), Ivoclar digital dentures (Ivoclar Vivadent Inc., Schann, Liechtenstein), Ceramill full denture system (Amann Girrbach, Keblack, Austria), Vita Vionic denture system (Vita Zahnfabrik, Bad Säckingen, Germany), Baltic denture system (Merz Dental GmbH, Lütjenburg, Germany), Zirkonzahn denture system (Zirkonzahn, Gais, Italy), on subtractive manufacturing side (Baba et al, 2021, Schweigera et al, 2018). On additive manufacturing side, Dentca CAD/CAM dentures (Dentca Inc., Los Angeles, CA), Fotodent (Dreve Dentamid, Unna, Germany) provide a 3D printed final prosthesis (Baba et al, 2021, Schweigera et al, 2018).

Even with the various advantages of available CECD systems, Steinmassl et al (2017) reminded all the dental providers to base the selection of a CECD fabrication system on provider's prosthodontic experience and patient requirements. This has been reiterated in another systematic review where authors concluded that CECDs are revealing positive outcomes, but this favourable trend is very dependent upon proper patient selection (Kattadiyil et al, 2017).

With a clear understanding of the indications, limitations, and workflows; digital denture prosthodontics can be predictably and profitably incorporated into clinical practice leading to improved patient satisfaction and favourable long-term outcomes (Maragliano-Muniz et al, 2021).

iv. Reline materials

Denture reline has been described as "the procedures used to resurface the intaglio of a removable dental prosthesis with new base material, thus producing an accurate adaptation to the denture foundation" (GPT-9). This alteration of the intaglio surface is required to ensure proper fit, enhance stability and function of the prosthesis during its service life (Anusavice et al, 2012).

iv(a). Rationale for use of denture lining materials

Residual ridge resorption is an inevitable consequence of tooth loss (Atwood et al, 1971). We now know that loss in height of anterior mandible after extractions can be as much as 4mm in first year and up to 7mm after 5years (Carlsson et al, 1967). Soft tissue contour changes following continued resorption of residual ridges; and when severe enough; will be detrimental to harmonious fit of denture base (Darvell et al, 2000). These authors themselves had also concluded that intimate denture base adaptation is one of the most important factors in denture retention; other being good peripheral border seal (Darevell et al, 2000). Maintenance of close adaptation of the denture base to the underlying mucosa covering the residual ridges necessitates alteration of intaglio denture surface and is thus described as a critical part of complete denture service (Pow et al,1998).

Denture relining involves replacement of tissue surface of complete denture to refit the intaglio surface to altered state of denture bearing surface (Zarb et al, 2013). It is safe to assume that failure to provide compensation for residual ridge resorption through retrofitting of existing complete dentures on a continuous timely manner will lead to ill-fitting dentures. Ill-fitting CRDP's have been linked to clinical findings like epulis fissuratum, inflammatory papillary hyperplasia, denture sore mouth or denture abused mucosa (Miller et al, 1977).

Denture reline procedure allows clinician to make additions to the intaglio of an existing CRDP, thus, improve fit of a CRDP by providing a much closer adaptation to the resorbed residual ridge underneath (Haywood et al, 2003). This refitting of existing denture becomes especially important in conditions where fabrication of a new denture may not be indicated or feasible as a result of affordability issues for the patient.

Barco et al (1979) found in their study that relining conventionally processed CRDP with auto-polymerizing acrylic resin improved their adaptation to the residual ridges and lead to better stability. Improvement in CRDP's fit as a result of denture relining procedure thus, will in turn positively affect its retention, stability and support (Rashid et al, 2015).

Implants assisted overdentures have been recognized as standard of care in management of edentulous mandible (McGill Consensus Statement, 2002). They have been recommended in management of patients with advanced residual ridge resorption (Cooper et al, 2008). Pham et al (2022) demonstrated that posterior ridge resorption even in presence of 2 implant assisted overdenture increases strain on these implants. This strain was only reduced by relining the overdenture (Pham et al, 2022). Thus, its safe to say that implant retained overdentures still require reline materials and it has been found that reline is mostly required in these patients in response to complaints of food accumulation underneath prosthesis (Attard et al, 2004). In a study on overdenture service needs, denture reline was found to be the second most commonly needed treatment (76.9% of patients required reline) (Ettinger et al, 2019). In another study, it was found that this patient pool with implant overdentures required laboratory processed relines on average every 4.40 years (Attard et al, 2004).

"Servicing" of complete denture involves not only a refitting of the impression surface of the denture base but also include occlusal corrections and a minor spatial reorientation (Zarb et al, 2013). It has been suggested that reline of an existing CRDP with a denture liner can help address issues of an ill-fitting denture in a relatively inexpensive and easy manner (Choi et al, 2018). Kreve et al (2019) recommended denture reline procedures as they are relatively quick and cheaper procedures which allow continued use of existing dentures.

iv(b). Advantages of denture liners

Denture lining procedures have been described to be capable of offering an immediate and relatively inexpensive reconditioning procedure to improve the fit of the intaglio denture base to the underlying denture bearing mucosa (Arena et al, 1993). Improved fit will also result in trends of increased stability of the relined denture base (Barco et al, 1979). It has also been claimed that relining materials help prolong the serviceable life of an exiting CRDP that is otherwise in a reasonable condition (Haywood et al, 2003). Reline are non-invasive and relatively economical procedures compared to remaking a denture (Kreve et al, 2019). Additionally, chair side hard denture line materials can also be used to make minor repairs to the denture as well (Haywood et al, 2003). It has been previously shown that relining of a poorly fitting denture will increase patient masticatory performance and lead to overall reduced chewing times (Garrett et al, 1996). This has also been supported more recently in a systematic review to evaluate effects of soft denture liners on masticatory performance of edentulous patients wearing CRDPs (Palla et al, 2015). Authors concluded as a result of their systematic review, that soft denture liners, especially long-term silicones, significantly improved masticatory function as compared to conventional denture base materials (Palla et al, 2015).

iv(c). Indications of denture liners

Indications for use of a denture liner may include need to enhance fit and retention of existing complete dentures, use as a diagnostic adjunctive for correction of occlusion or recovery of vertical dimension, relief, and recovery of tissues by use as a tissue conditioner, to provide relief from pain and soreness and to help in retention of maxillofacial prosthetics (Zarb et al 2013).

iv(d). Contraindications of denture liners

Ortman et al (1975), reviewed concepts and materials in denture refitting. Use of denture liners may be contraindicated when there is a great loss of vertical dimension of occlusion with existing CRDP, unacceptable esthetics or plane of occlusion, underlying tissues have been greatly altered due to resorption or surgeries, denture occlusion cannot be equilibrated, and finally denture base is severely underextended (Ortman et al, 1975). A loss of vertical dimension greater than 3mm or lack of interocclusal space have also been enumerated as possible contraindications to reline procedures (Kubo et al, 2014).

iv(e). Disadvantages of denture liners

Reline materials do have some disadvantages as well.

Haywood et al (2003) in their study on chair side hard liners stated that reline materials suffer from monomer release which may lead to foul taste or odour. Also, as polymerization of direct hard reline materials is through an exothermic reaction, it can lead to burning sensation in some patients. This intra-oral increase in temperature with polymerization was also enlisted as a disadvantage of direct hard liners (Brauer et al, 1959).

Denture liners are described as facilitating fungal adhesion and colonization which may lead to palatal mucosal injury and even denture stomatitis (Masetti et al, 2018). Delamination of reline materials due to possible saliva penetration (Haywood et al, 2003), porous structure, water solubility, compromised hardness, and transverse strength values (Brauer et al, 1959) have also been enlisted as inherent problems that compromise long term clinical serviceability of denture reline materials. Kreve et al (2019) summarized disadvantages of various denture lining materials currently available in their systematic review. Some of these disadvantages may be unique to resilient liners but some may also be common to all reline materials. These include failure of adhesion, presence of surface defects, a rougher surface, changes in hardness, residual taste, tendency to pick up stains and odours, water sorption, proneness to colour change, difficulty in cleaning, leaching of plasticizers, reduced strength of denture bases and concerns about biocompatibility (Kreve et al, 2019).

iv(f). Timing of reline procedures

Felton et al, concluded in 2011, that there are no evidence-based set clinical guidelines to help determine on frequency of relining and rebasing procedures (Felton et al, 2011). There have been some recommendations made by some authors on this exact topic which can be found in the literature. A handy guideline can be to assess CRDP wearing patients annually to monitor for residual ridge changes and resultant denture base maladaptation can thus be identified (Kubo et al, 2014). Cooper, L.F. concluded in 2009 that on average CRDP require relining every 4 years (Cooper et al, 2009). As previously discussed, implant retained overdentures also require reline materials and it has been found that reline is mostly required in these patients in response to complaints of food accumulation underneath prosthesis (Attard et al 2004). More interestingly, even this patient pool with implant overdentures required laboratory processed relines on average every 4.40 years (Attard et al, 2004). This is surprisingly similar to reline intervals for conventional CRDP.

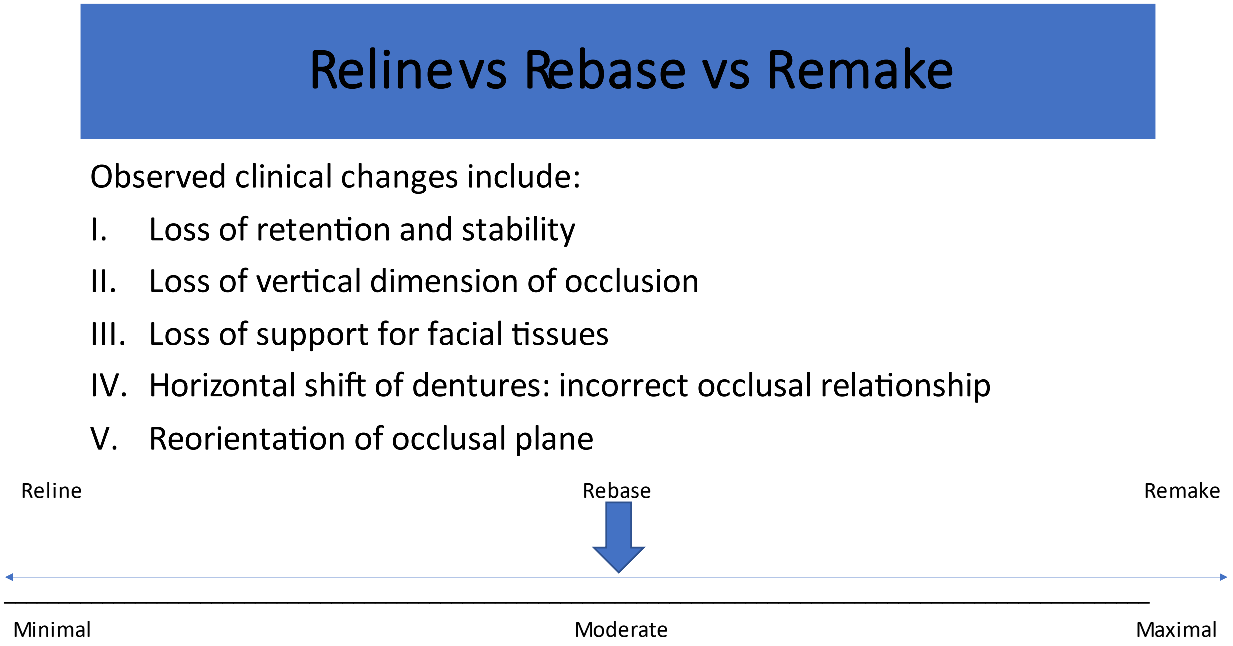
In a long-term retrospective study, up to 83% of laboratory processed silicone-based liners were found to be serviceable at 6 years of use (Schmidt et al, 1983). Another suggestion was provided on denture liner interval by Kubo et al in 2014. They recommended a direct resilient reline every 1 to 4 months in cases of immediate CRDPs or after surgery for patient comfort, in case of a conventional CRDP. In use CRDP should preferably be laboratory processed relined every 1 to 5 years based on patient factors and prosthesis factors (Kubo et al, 2014).

iv(g). Decision between relining versus rebasing versus remaking a CRDP

Given there are so many potential disadvantages with denture lining materials, and it is a very technique sensitive procedure to undertake. A prudent practitioner may question the need to reline an existing CRDP at all and instead may devote efforts into rebasing an existing CRDP or entirely remaking the CRDP.

Rebasing is described as "laboratory process of replacing the entire denture base material on existing prosthesis"; by Glossary of Prosthodontic terms (GPT-9).

Zarb et al (2013) provided this valuable decision tree (figure 2) to distinguish the need to reline versus a rebase based on a through clinical exam after understanding patient complaints. Given that rebasing has similar challenges to denture relining and additionally laboratory costs for a denture rebase can be significant, so that remaking a CRDP may be a similar or better alternative to rebasing.



Reline vs Rebase vs Remake

Observed clinical changes include:

I. Loss of retention and stability
II. Loss of vertical dimension of occlusion
III. Loss of support for facial tissues
IV. Horizontal shift of dentures: incorrect occlusal relationship
V. Reorientation of occlusal plane

Figure 2. Decision tree to decide between reline, rebasing, or remaking {Adapted from Zarb et al, 2013}

Selection of a patient for denture relining must be an objective clinical decision. A prudent clinician will specifically consider if a complete denture will be relined or should be remade (Jumbelic et al, 1984).

To effectively soft reline an existing denture one must start with a CRDP that is stable, in good occlusion and well made (Murata et al, 2008). It is important to note that a wrongly designed and fabricated CRDP cannot be corrected by relining or rebasing procedures and must be remade (Hawkins et al, 1948).

Pow et al (1998) comparatively evaluated linear dimensional change of heat-cured acrylic resin complete dentures after relining and rebasing procedures. It was concluded in this study that rebasing lead to significantly more warpage of denture base as compared to indirect reline procedures. This dimensional change is due to release of inherent residual stresses during denture base processing. It is important to note though that these resultant dimensional changes may be small in magnitude (0.1%) and can be clinically corrected by occlusal adjustments and close fitting of denture base after second processing (Pow et al, 1998). Another group of authors cautioned against extensive additions with soft lining to an existing denture base due to resultant decrease in yield load and increased denture deflection due to plasticizing effects of soft lining materials

(Davis et al, 1988). Moreover, if esthetics of the existing CRDP are unacceptable or if the occlusal relationship cannot be corrected by equilibration; remaking of the CRDP is the only practical alternative. Thus, unacceptable esthetics or occlusal relationships may be considered absolute contraindications to a rebasing procedure. Due to complexity of relining procedures, it can be safely said that often times a remake may be a better option as compared to relining an ill-fitting denture (Bowman et al, 1977).

iv(h). Classification of denture liner materials

As there are many different indications for denture relining procedure; no single denture liner material is able to service all the clinical situations demanding its use. As such there are multiple different types of denture lining materials that have been formulated. Broadly speaking denture lining materials may be classified into a hard denture liner or a soft/ resilient denture liner (figure 3).

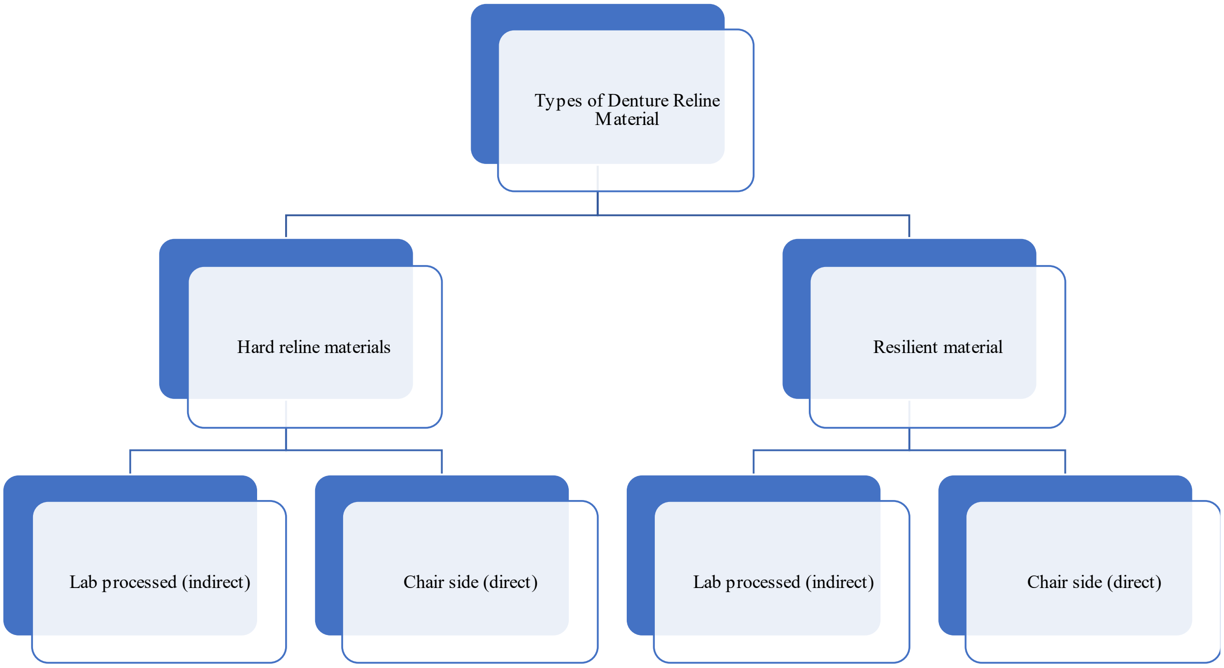


Figure 3. Classification of denture reline polymers {Adapted from Kreve et al, 2019}

Both hard and soft reline materials vary in their handling, properties, and longevity. Indirect relines or "mediate relines" require clinical impression procedures and laboratory heat processing steps.

While direct chair side reline materials or “immediate relines” are comparatively easier and quicker to use (Kreve et al, 2019). It has been stated that direct chair side denture liner materials, both hard and soft, may release more monomer than laboratory processes hard and soft denture liner. Increased monomer release is associated with certain disadvantages of direct chair side relining materials like foul taste and mal odours with use (Haywood et al, 2003). Indirect relining methods which have been also described as “mediate reline procedures” (Kubo et al, 2014); lead to less residual monomer. This reduced monomer release is thought to be a result of heat processing involved with laboratory processing and lead to better stability and superior durability (Haywood et al, 2003). Some authors have also suggested that “mediate” lab processed relining is better than “immediate” direct chair side relining procedures due to increased durability of materials employed and lower porosities (Kubo et al, 2014). This was also supported in another study where indirect laboratory processed method of soft denture reline was deemed to be more favourable than direct chair side soft reline methods and materials (Murata et al, 2008).

It is important to note that heat processing will lead to non-significant shrinkage during reline procedures which may necessitate some refinement of occlusion and adjustments at time of relined denture delivery (Pow et al, 1998). Thus, a proper technique selection and utilization of proper processing methods for liner material selected are critical to success and longevity of results (Schmidt et al, 1983).

Potential problems with monomer release, malodours, foul taste, durability, and stability have led to the general consensus among researchers that direct chair side reline materials are not adequate for long term clinical service of denture patients (Brauer et al, 1959). Most of the authors agree that direct chair side reline materials should be thought of as being transient in nature. Takahashi et al (2001) claimed that only service provided by direct chair side denture reline polymers is to retrofit an existing CRDP while patient is waiting for a new prosthesis.

iv(i). Hard denture reline materials

Direct chair side hard reline materials offer an immediate and rather inexpensive reconditioning of an ill-fitting prosthesis (Arena et al, 1993). Hard reline materials have problems of porous structure, water solubility, compromised hardness, and compromised transverse strength values.

Thus, it was concluded that due to these inherent problems, hard direct reline materials should only be considered temporary treatments though (Brauer et al, 1959). Saliva penetration during chair side hard reline procedure may interfere in its adherence to the denture base, but this may be reduced by use of adhesives on denture base (Haywood et al, 2003).

Hard reline materials are overwhelmingly either PMMA or its copolymer PEMA (polyethyl methacrylate) based. Direct chair side hard liner materials are also available as visible light-cure (VLC), which mostly consist of a urethane dimethacrylate (UDMA) matrix and acrylic copolymers along with a photo-initiator (Arena et al, 1993).

In a systematic review on cytotoxicity of denture resin polymers it was indicate that hard denture liners may have some undesirable interactions with underlying denture supporting tissues (Chaves et al, 2012).

iv(j). Resilient denture reline materials

Resilient denture liner is defined as an "interim (ethyl methacrylate with phthalate plasticizers) or definitive (processed silicone) liner of intaglio surface of removable complete or partial dentures or intra-oral maxillofacial prosthetics" (GPT-9).

Resilient denture liners are generally preferred over hard reline materials by patients (Wright et al, 1980). Their use is very popular in patients who cannot accommodate the hard denture surface against thin atrophied denture bearing ridges or mucosa due to increased comfort (Kreve et al, 2019). International Standard Organisation in 1999 defined soft denture lining material as a soft resilient material bonded to the fitting surface of a denture to reduce trauma to the supporting tissues (Hashemi et al, 2015).

It has been estimated that approximately 5% of all mandibular complete denture wearers utilize some kind of soft liner for comfortable function of their prosthesis (Wright et al, 1981). Their popularity may be attributable to the fact that resilient denture lining materials are used to form a cushioning layer between hard denture base and load bearing oral mucosa to help in more even distribution of forces and absorption of some of these forces (Hameshi et al, 2015). It was shown in a clinical investigation on effects of resilient lining materials of denture bases, that these resilient liners effectively manage pain on residual ridges in severely atrophic mandible (Emura et al, 1992).

Pain relief with soft liners is thought to result from their action as shock absorbers which allows a more uniform stress distribution and reduce discomfort (Sinobad et al, 1992).

Viscoelastic properties of the soft liner characterize their relative ability to temporarily deform by absorbing impact forces during mastication (Pesun et al, 2001). Soft lining materials do not reduce the transmitted force but instead because of their complaint nature, they help to evenly distribute these forces leading to smaller displacement of oral mucosa (Demir et al, 2011). Compliance is a measurement of the softness or flexibility of a material (Pesun et al, 2001). Resilience of a material is defined as "capability of withstanding shock without permanent deformation or rupture or tending to recover from or easily adjust to change" (GPT-9).

Soft liners by virtue of their viscoelastic properties like resilience and compliance, help alleviate pain for so many denture patients. It is no surprise then, resilient liners are indispensable for patients requiring immediate dentures or with healing ridges after surgery or denture patients who brux on atrophied ridges (Hashemi et al, 2015). In a long-term retrospective study, it was determined that a vast majority of patients (93%) felt more comfortable with a soft lined denture. It was also concluded in the same study that an overwhelming number of patients (95%) would elect their new dentures to be soft relined (Schmidt et al, 1983).

Resilient liners can help better adapt a CRDP to the underlying denture supporting tissues and thus, positively influence stability of the prosthesis. At the same time, resilient liners also help condition underlying denture bearing mucosa (Kubo et al, 2014).

On other hand, it has been argued that denture base and overlying reline material bear and resist the masticatory load as a whole, rather than the reline alone (Takahashi et al, 1998). To address this question regarding ability of resilient liner materials to increase chewing ability and providing comfort to patients a systematic review was conducted by Palla et al (2015). These authors found that soft denture liner's efficacy in improving masticatory function of patients wearing CRDP is closely related to patient comfort while functioning. Authors concluded that soft denture liners, specifically long-term silicones, indeed do improve the masticatory function compared to conventional denture base materials (Palla et al, 2015).

Murata et al (2008) also previously had investigated clinical efficacy of soft denture liners. They extoled that viscoelasticity of soft liners is the property which alleviates patient discomfort. Authors also suggested soft denture liners will be most efficient if Young's Modulus of a resilient liner was kept close to that of oral mucosa (Murata et al, 2008). This notion on the other hand was countered by another group, who suggested that if long term soft liners had compatible viscoelasticity to oral mucosa, then a reduction in shape recovery of the material is to be expected. This in turn will reduce soft liner's ability to cushion and relieve pain (Chladek et al, 2014). This line of thinking has been supported by Braden et al in their 2012 book on polymeric dental materials. Authors suggested that denture liners will only absorb energy and deform under occlusal stresses, if their stiffness is less than that of the underlying mucosa (Braden et al, 2012). Importance of maintaining soft denture liners elasticity is thus critical to their prolonged clinical use and surface sealants may help in achieving this goal by preventing water absorption and leaching of plasticizers (Kreve et al, 2019).

An added benefit of soft denture liners is their ability to engage undercuts which is especially advantageous in patients with maxillofacial defects (Mack et al, 1989).

Lammie and Storer (1958) lamented lack of more widespread use of this excellent treatment option for a wide variety of CRDP wearers who can benefit greatly from use of resilient denture base materials. These authors contributed this limited use of soft denture liners to lack of a suitable material (Lammie et al, 1958).

Many kinds of soft denture liners have been developed with varied applications to address different clinical situations face.

1. Classification of resilient denture liners

Soft liners fall into two main categories of temporary soft liners and permanent soft liners (Murata et al, 2002). Based on their chemical structure, they may also be divided into four groups of plasticized acrylics, vinyl resins, polyurethane and silicone rubbers (Muddugangadhar et al, 2020). Based on polymerization method they may be classified as heat cured, auto polymerized or visible light cured resilient liners (Kreve et al, 2019). This differentiation of resilient liners is shown in figure 4.

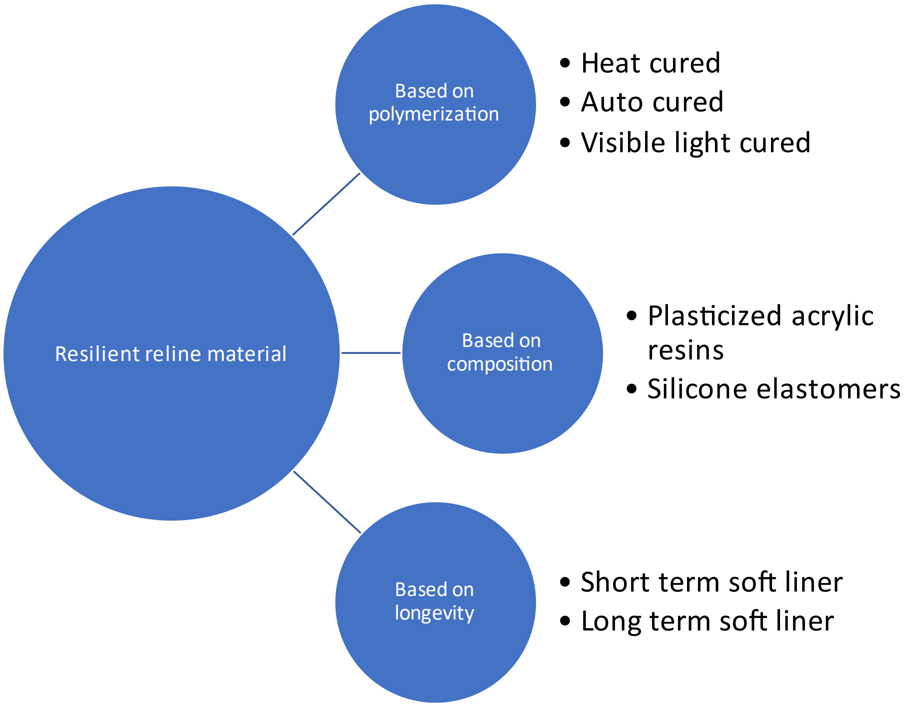


Figure 4. Classification of resilient denture reline polymers {Adapted from Kreve et al 2019, Murata et al 2008}

2. Visible light cured denture lining

VLC denture lining materials are polyurethane based and thus are not compatible with the chemistry of the commonly used denture base polymers. These denture liner materials hence require an adhesive agent to predictably bond to different denture bases (Takahashi et al, 2001). It has been suggested that visible light cured denture liner formulations have some advantages over traditional plasticized acrylic denture liners such as reduced chemical irritation, ability to use them in patients sensitive to monomer and easier handling among others (Zarb et al, 2013). Zissis et al (2001) concluded that VLC lining materials have better wetting properties leading to better denture retention and patient comfort as an added benefit.

3. Short-term soft denture liners (Tissue conditioners)

Short-term soft denture liners are intended for use up to 30 days only (Kreve et al, 2019).

Their clinical use was first described by Chase et al in 1961, while their structure was first described by Braden et al in 1970. While discussing clinical application of tissue conditioners, most authors recommended their replacement every 2-3 days (Chase et al, 1961). Their use for functional impression was arguably first described by Smith et al (1965). These authors called this technique at the time a final dynamic impression utilizing a dynamic adaptive stress (Smith et al, 1965). If tissue conditioners are being used for functional impressions, then a 24-hour wear of tissue conditioned denture was recommended (Braden et al, 1995).

Tissue conditioners typically are much different than crosslinked polymers and for practical purposes should be considered viscoelastic gels (Wright et al, 1981). Tissue conditioners have been described as non-cross-linked amorphous polymers (Maeda et al, 2012). Tissue conditioners contain polyethyl methacrylate as basic polymer and a liquid containing ethyl alcohol as a solvent and dibutyl phthalate as a plasticizer. Tissue conditioners are devoid of a methacrylate monomer (Anusavice et al, 2012, Zarb et al, 2013). Even with these excellent properties and ease of use, tissue conditioners are recommended to be only used in carefully selected patients (Nassif et al, 1984).

One of the most remarkable features of tissue conditioners is their high viscoelasticity but early and high loss of plasticizers into aqueous environment (Wright et al, 1981).

4. Long term soft denture liners

Long term soft denture liner are polymer materials that are designed for intra-oral use for more than a month but can last longer even up to years (Zarb et al, 2013). They may be classified as acrylic based or silicone based long term soft denture lining materials (Chladek et al, 2014).

4(a). Plasticized acrylic based resilient denture liners

Plasticized acrylic-based long-term soft denture lining materials (ABLTDL) are usually a two-component powder liquid system similar to autopolymerizing denture base resins with added plasticizers like dibutyl phthalate or ethyl acetate (Anusavice et al, 2012). Plasticizers work by separating polymer chains and lowering glass transition temperature and thus soften the set material (Chladek et al, 2014). Glass transition temperature needs to be lower than mouth temperature so that the ABLTDL polymer which exists as a powder at room temperature can be converted into a viscous gel inside the mouth (Braden et al, 2012). Though it is important to note that plasticizers in ABLTDL materials are not bound and are thus susceptible to leaching which is cause for their rapid loss of viscoelasticity thus limiting their clinical life (Maeda et al, 2012). Other leachable compounds in plasticized acrylics include monomers, reaction by products like benzene, toluene, phenolic compounds (Chladek et al, 2014).

Generally, plasticized acrylic-based long term liner materials are less resistant than silicone based long term reline materials and as such show slow response to occlusal loads and are slower to recover to the original dimensions as well (Wright et al, 1981).

An added benefit to plasticized acrylics is their similar chemical structure and polymerization reaction to PMMA based denture base polymers. Thus, a much stronger bond between two can be elicited if proper relining protocols are followed (Özdemir et al, 2018).

On the downside, it has been purported that plasticized acrylic-based long-term denture liners may be rougher than their silicone-based counterparts due to their polymerization method, residual monomer, and eventual plasticizer leaching (Kreve et al, 2019). It has been shown that initial roughness of these materials can be as high as 3.54 µm and disinfection protocols can often increase this surface roughness over time (Machado et al, 2009)

Chemical Composition of Plasticized Acrylic Based Resilient Denture Liners
Short-term resilient liner (Tissue conditioner): Autopolymerizing Powder. Liquid System Powder: poly ethyl methacrylate Liquid: lacks a methyl methacrylate monomer Solvent: ethyl alcohol Plasticizer: aromatic ester (like dibutyl phthalate)
Long-term resilient liner: Heat activated Powder: Liquid System Powder: poly ethyl methacrylate Initiator: benzoyl peroxide Liquid: methyl methacrylate monomer Plasticizer: phthalate ester
Long-term resilient liner: Auto-polymerizing Powder: Liquid System Powder: poly ethyl methacrylate Initiator: tertiary amine system Liquid: methyl methacrylate monomer Plasticizer: phthalate ester

Table 2. Chemical composition of acrylic based resilient denture reline polymers {Adapted from Zarb et al 2013}

4(b). Silicone based resilient denture liners

Silicone based long term soft denture lining materials have been classified as autopolymerizing (RTV- room temperature vulcanized) e.g., Sofreliner Tough S or as high temperature vulcanized (HTV) e.g., Molloplast B (Chladek et al, 2014).

RTV or autopolymerizing silicone lining materials are generally 2 paste system with base paste containing a vinyl terminated polydimethylsiloxanes and a catalyst paste consisting of a hydride terminated polydimethylsiloxane with platinum catalyst. HTV or heat processed silicone-based liners are a single paste system consisting of polydimethylsiloxanes with an organic peroxide like benzoyl peroxide (Anusavice et al, 2012, Chladeck et al, 2014).

Chemical Composition of Silicone Based Resilient Denture Liners
High temperature vulcanized (HTV) silicones: Single component paste system Paste: α,ω-divinyl polydimethylsiloxane Filler: Silicon dioxide Initiator: Benzoyl Peroxide
Room temperature vulcanized (RTV) Silicones: Two component paste system Paste: α,ω-divinyl polydimethylsiloxane Filler: Silicon dioxide Catalyst: Platinum Adhesive Primer: Ethyl acetate Adhesive polymer

Table 3. Chemical composition of silicone based resilient denture reline polymers {Adapted from Zarb et al 2013}

Silicone rubbers are considered most successful soft denture liners as they retain their elastic properties longer (Demir et al, 2011). This has led to their increased popularity and a recent systematic review evaluating bond strengths of resilient lining materials also concluded them to be most commonly used resilient denture lining materials (Özdemir et al, 2018). But their bond strengths are considered inferior to plasticized acrylics due to different chemical composition than most PMMA dentures (Chladek et al, 2014, Özdemir et al, 2018). However, with use of proper adhesives it has been shown that bond strength between silicone based resilient liners is durable enough for 3 years of clinical use (Murata et al, 2008). This adhesive normally consists of an organic solvent and a monomer which will dissolve PMMA and react with both silicone and resin materials (Demir et al, 2011, Muddugangadhar et al, 2020).

It has been postulated that filler constituents in silicone-based long term denture liners are responsible for their water sorption (Braden et al, 1983). Silicone based resilient liners seem to have significantly small changes in viscoelastic properties even after 3 years of storage (Murata et al, 2008). Direct chair side silicone liners still suffer from high water sorption, poor dimensional stability and rupture properties and should not be considered a permanent solution (Wright et al, 1981).

Moreover, silicone lining materials have very low transition temperature and thus are not very sensitive to intra oral temperature changes (Demir et al, 2011).

5. Properties of resilient denture liners

Ideal properties of a resilient denture liner should include good cushioning effect with long term dimensional stability (Pesun et al, 2001). Permanent resiliency, minimal to no fluid sorption and liner material inherently being inhibitory to fungal growth are also desirable (Pesun et al, 2001). For ease of processing, these materials should also be easy to trim, adjust, finish, polish, and have excellent bonding capabilities to different denture bases (Hameshi et al, 2015).

None of the current materials have all these properties, but this is not a new problem. Wright in 1976 described soft lining materials as being inadequate to their requirements despite their widespread use.

Combe and Grant in 1973 suggested that resilient lining materials are so deficient in their properties that even though they are intended for permanent use they should only be considered “semi-permanent”.

Some of the properties of current soft denture liners are as following.

5(a). Strength of relined denture base

Often denture base needs to be reduced in bulk to accommodate for the soft lining material which may lead to denture base fractures (Mack et al, 1989). It has been advised that soft lining materials may not be advisable for use if interalveolar space is less than 5mm (Mack et al, 1989). This basically limits resilient denture liner use predominantly to mandibular removable dentures.

Higher amounts of plasticizers can be detrimental to the transverse strength of the denture base. It has been suggested that as plasticizers leach out of liner material, they may interact with surrounding denture base, thus, lowering its strength (Brauer et al, 1959). There was an interesting study looking into plasticizing effects of temporary soft lining materials on polymerized acrylic resins (Davis et al, 1988). Authors found that denture deflection under load after relining may increase by 100% because of softening of the denture base due to resilient relining procedure. This plasticizing effect was much more pronounced in autopolymerized acrylic denture bases but was present to a much lesser extent in heat cured acrylic denture bases (Davis et al, 1988).

Strength of a relined denture base polymers is found to be dependent upon the strength of the denture base itself and also on the inherent strength of the lining material (Takahashi et al, 2000). Water sorption by the denture base and liner has been shown to lower the flexural strength of the relined denture bases as well (Takahashi et al, 1998).

In a study on effects of reline materials on impact strength of dentures, authors concluded by saying that impact strength will depend upon type of denture reline material chosen and type of surface treatment utilized (da Cruz et al, 2010). More interestingly, it was also found in another study that strength of the denture base that is being relined may also be affected by the bond strength between the liner and the denture base (Takahaski et al, 2001).

5(b). Bonding mechanism of denture base to the liners

An adequate bond between denture base and reline material is required for retention of reline material (Chai et al, 1998). Bond strength between liner and denture base can also affect the overall strength of relined denture base (Takahaski et al, 2001). It stands to reason that a poorly adherent denture liner will thus be more likely to adhesively fail at a lower stress during function (Chai et al, 1998). A poor bond between denture base and liner not only leads to delamination of the lining material but may also lead to percolation of saliva and create an ingress point for microbial flora (Takahashi et al, 2001). Loss of adhesion has been cited as the most common reason for failure of soft lined dentures by Wright in 1983 and same was more recently concluded through a systematic review by Kreve et al (2019).

Mechanism of liner adhesion involves solvent or monomer in the reline material swelling the denture PMMA surface, diffusion of liner monomer into this swollen denture base surface and a subsequent polymerization of interpenetrating polymer network (IPN) (Kim et al, 2014). Larger the surface swelling, deeper the porous layer, better penetration of monomer and consequently better adhesion between denture base and liner (Kreve et al, 2019). A mutual solubility or compatibility of the denture base polymer and the overlying liner polymer, along with an intimate contact between two during chemical interaction of bonding reaction are essential to establish the interwoven IPN connection (Takahashi et al, 2000). PMMA based denture reline materials have been shown to bond stronger with PMMA denture bases due to similar chemistry (Arena et al, 1993). Thus, it stands to reason that additively manufactured denture bases may not bond as efficiently to plasticized acrylic or silicone denture liner materials due to difference in their chemical structure and polymerization reactions. Recently, a comparative study evaluating bond strength between conventional, milled, and printed denture bases, showed some surprising results (Wemken et al, 2021). In this study, 3D printed denture bases performed equally well and even showed improved bond strengths to denture reline materials (Wemken et al, 2021).

It was concluded in another study on bond strengths of denture liners to the underlying denture bases that type of these two polymers and their interactions will affect bond strength between them (Takahashi et al, 2001). Penetration of solvent or monomer may not be as effective with highly cross-linked denture bases (Takahashi et al, 2001). Thus, it stands to reason that a highly cross-linked denture base such as prepolymerized PMMA in a milled CECD may not show adequate adhesion with denture lining materials. However, subtractively manufactured denture bases showed similar bond strengths to soft reline materials as compared to conventional PMMA denture bases and surprisingly higher bond strengths to tested hard reline materials (Wemken et al, 2021).

It can be safely concluded that bond strengths are affected not only by material characteristics of denture base and relining polymers but also the adhesives being used (Choi et al, 2018). This has also been previously concluded by another study where authors concluded that failure mode of the resilient liners closely depends on the adhesive used (McCabe et al, 200).

VLC denture bases restrict movement of monomer and thus theoretically should limit ability of a resilient liner to bond with them (Takahashi et al, 2000). Similarly, successful reline of polyamide denture base resins is suspect as bond strength between these materials has never been clearly investigated and choice of reline materials for polyamide denture bases is based on clinician preference (Kim et al, 2014).

Different surface treatment methods have been described in literature to increase bond strength between different resilient liner and denture bases. Adhesive bond strengths between denture base and liner polymers can be improved by wetting denture base with monomer or other organic solvents (Kim et al, 2014). This was supported in another in vitro study evaluating effects of surface treatments on adhesion of silicone based reline materials. It was shown that tensile bond strength of reline material to PMMA denture base increased over 45% with application of MMA monomer and ethyl acetate. It was thought that this increase was possibly explained partly by higher surface roughness created by these surface treatments leading to better mechanical adhesive penetration and interlocking (Cavalcanti et al, 2014).

Surface treatments with lasers increase surface roughness and thus result in greater treated denture surface area available for bonding, which consequently leads to increased penetration of the liner (Muddugangadhar et al, 2020). Other surface treatments capable of enhancing denture liner adhesion include oxygen plasma pretreatment, acid etching (Kreve et al, 2019, Ozdemir et al, 2019). Interestingly, airborne aluminium particle abrasion led to reduced bonding strengths (Muddugangadhar et al 2020). Authors postulated that it may be explained due to creation of internal stresses as a result of airborne particle abrasion (Muddugangadhar et al 2020).

Özdemir and Özdoğan (2018), systematically reviewed bond strength of resilient lining materials to denture base resins. They concluded that overall acrylic based resilient lining materials showed higher bond strength values than silicone- based lining materials; while chemical agents and MMA monomer were most effective surface treatments to increase bond strength (Özdemir et al, 2018).

Old dentures may be more difficult to reline as micro-organisms on the denture surface produce methyl mercaptan by-products which will cause delamination even after primary dissolution. It has been recommended to remove up to 3mm of denture intaglio surface so as to prevent this complication (Kreve et al, 2019).

An improvement in bonding durability of the soft liners will not only reduce migration of saliva and other fluids into the interface but will also improve microbial resistance of the liner (Chaldek et al, 2014).

Demir et al in their 2011 study concluded that heat processed single tube silicone denture liner systems when packed against uncured PMMA dough showed highest boned strengths.

Despite all these possible shortcomings and potential problems with bonding, it seems like adhesive strength between silicone-based long-term resilient liners is durable enough for 3 years of clinical use (Murata et al, 2008).

5(c). Microbial adhesion to resilient liners

Denture liner materials, especially resilient liners, have surface irregularities and micro-porosities that facilitate fungal adherence and colonization on the lining material (Masetti et al, 2018). It was concluded in a systematic review that failure of adhesion, rough surface characteristics are all conducive to microbial colonization of resilient liners (Kreve et al, 2019). Quirynen et al (1990) suggested that no bacterial adhesion may occur if surface roughness is less than 2 µm. It has been shown that initial roughness of plasticized acrylic based soft denture liner materials can be as high as 3.54 µm and disinfection protocols can increase this roughness over time (Machado et al, 2009). This porous and rough surface of soft reline materials will not only enhance candida adherence via plaque and biofilm formation it also allows for ingress and entrapment of fugal cells into the reline material itself (Pereira- Cenci et al, 2008). Soft reline materials have thus been purported to be convenient ground for microbial colonization as compared to denture bases themselves or even hard reline materials (Bulad et al, 2004). Saliva and salivary proteins promote this microbial colonization of the denture lining materials (Chladek et al, 2014).

Colonization by fungi and other microbiota is a common problem for both direct and indirect liner materials. In a review of long-term soft denture liners, it was suggested that presence of fungal colonies was particularly problematic and could be found in 44% of the long-term soft lining samples (Chladek et al, 2014). About 28.2% of sampled heat processed silicone based resilient liners (Molloplast B) on long term denture wearers tested positive for yeasts in a 6 year long retrospective study (Schmindt et al, 1983). Weakened adhesive bond between denture and liner material also allows percolation of oral fluids and ingress of microbiota (Takahashi et al, 2001). Microbial colonization of an old and existing dentures can lead to disruption of adhesion between liners and underlying denture bases through production of methyl mercaptan (Kreve et al, 2019).

Skupien et al (2013) concluded through their systematic review that 0.5% sodium hypochlorite immersion and microwave irradiation could help disinfect denture liners and tissue conditioners. Alternatively, authors recommended 500000 units of Nystatin could be incorporated into the tissue conditioners to treat the condition (Skupien et al, 2013). Tissue conditioners admixed with anti-fungals and replaced every 2-3 days were suggested as an adjunctive in management of denture stomatitis (Braden et al, 2012). It has also been suggested that any antifungal can be incorporated into a soft reline material in treatment of candida denture stomatitis, without any detrimental effects to the adhesive bonding of the denture liner material (Alcantara et al, 2012). It has thus been suggested that frequently replaced soft reliners may be used in treatment of denture stomatitis in short term (Yarborough et al, 2016). It may be explained by better fit and adaptation of the denture to the underlying tissue and often replacement of the microbe laden reline materials may help reduce bioburden.

Microbial colonization of long-term soft denture liners was concluded to be one of the most common reason for their clinical failure accounting for 1 in 3 failures (Chladek et al, 2014).

5(d). Thickness recommended for resilient liners

It can be vexing to decide what thickness of resilient denture liner is required for them to be effective.

One of the very first studies looking into properties of resilient denture liners recommended a 2mm layer thickness of soft liner (Craig et al, 1961). These authors found resilience of soft liners to be a function of their thickness as well. It was concluded that a further increase in thickness after 2mm did not increase resiliency of the denture soft liner (Craig et al, 1961).

Compliance of resilient denture lining materials is very closely related to their thickness during function (Wright et al, 1980). Effect of liner thickness on their compliance was investigated by Pesun et al in 2001. These authors found that compliance of resilient liners did not improve after a liner thickness of 2.2mm and seems to level off at around 3.3mm. Thus, they recommended keeping resilient denture liner thickness between 2.5mm and 3.5mm (Pesun et al, 2001). McCabe et al on other hand concluded that lab processed silicone reline material can be in thickness of 2mm as beyond that their compliance did not change (McCabe et al, 1996). While Schmidt et al (1983) had previously recommended an optimum thickness of approximately 3mm for heat-processed long-term silicone-based liners. They did concede that thinner sections of soft liner could be used with less resorption though (Schmidt et al, 1983).

It has been suggested that patient comfort and resultant improvement in patient's masticatory function is a result of viscoelasticity of soft denture liners (Maeda et al, 2012). Combining various recommendations for resilient liner thicknesses in relation to their resilience and compliance, it is believed, a recommended thickness of 1.5 to 2mm for soft denture lining material can be effectively used in most cases (Murata et al, 2008).

5(e). Water sorption of resilient denture base liners

Diffusion of water molecules into denture base and liner resins will lead to a reversible change in their dimensions (Takahashi et al, 2000). Almost all soft denture liners have been shown to increase in weight with extended water storage (Craig et al, 1961). Relined dentures undergo two simultaneous processes during water immersion: water absorption and leaching of constituents (Braden et al, 1983). Generally, it is found that loss of plasticizer is much more pronounced as compared to ingress of water resulting in an overall increase of hardness of soft denture liner (Braden et al, 1995).

Compliance of lining materials is also affected by water storage as adsorbed water will act as plasticizer while leachable components will be lost, leading to ultimate loss of denture liner compliance (Braden et al, 1983). Water storage may also affect viscoelastic properties of lining materials, but this change seems to be small in silicone type resilient denture liners (Murata et al, 2008). This may be explained by the fact that only filler constituents which are present in very small quantities in silicone type liners are prone to water sorption (Braden et al, 1983).

Quantity of water sorption is dependent on material type and thickness, and it was concluded in a previous study that highly crosslinked denture bases and reline materials exhibit lower water sorption (Takahashi et al, 1998). Even though displacement of denture polymer chains with water causing expansion is reversible, it should be noted, that continuous wetting and drying will ultimately lead to irreversible warpage. Dimensional instability caused by water sorption creates strains at the adhesive bond interface between denture base and lining materials ultimately leading to their failure (Braden et al, 1983).

The diffused water molecule will generally act as a plasticizer and may decrease the overall strength of both the denture base and overlying reline resin polymers (Takahashi et al, 2000). An in-vitro study was conducted to check the effects of long-term water immersion on denture polymers. There was an overall decrease in the strength of all denture resins with water immersion (Takahashi et al, 2000). Conversely, it has been suggested that almost all resilient liners will absorb water and become stiffer with extended water absorption (Craig et al, 1961). Sinobad et al (1992) evaluated bond strength and rupture properties of resilient liners. An increase in peel bond strengths of the resilient denture liners was noticed after water immersion for 7 to 90 days (Sinobad et al, 1992). Increasing peel bond strength of resilient liner can be good in some instances as it may lead to an increase in retention and overall strength of the material but generally speaking this is achieved at sacrifice of liner resiliency and tear strength (Craig et al, 1961).

Water sorption also reduces flexural strength of tested relined denture bases (Takahashi et al, 1998). A study investigated effects of water immersion on flexural strength of relined denture bases. Decrease in flexural strength of relined denture bases after water immersion hastens as thickness of reline material increases (Takahashi et al, 1998). The effect of increasing thickness of reline material inversely affecting the flexural strength can be explained by possibly increased water sorption in the reline material with increased thickness. Clinically an ever-increasing reduction of denture base thickness will be required to accommodate for increasing thickness of denture liner. Wright et al (1980) studied rupture properties of denture soft lining materials. Tear strength of all reline materials deteriorated after 6 months of water immersion (Wright et al, 1980).

Interestingly most of these polymers will reach a state of equilibrium after which time strengths of denture base resins and liner polymers does not decrease with water immersion (Takahashi et al, 2000).

5(f). Bond strength testing for resilient liners

Originally Craig and Gibbons in 1961 had concluded that adhesion values of 10 pounds per inch were clinically sufficient. But current standard was established by Kawano et al in 1992 utilizing Craig et al study from 1961. It is now acknowledged that resilient denture lining materials require a minimum bond strength of 0.44 MPa to be clinically acceptable (Kawano et al, 1992).

Multiple tests like peel, tensile, shear, fatigue, creep, impact and cleavage have been devised over years to evaluate adhesive bond strengths of reline materials (Al-Athel et al, 1996). It has been concluded in a systematic review that test method has an important effect on the denture reline bond strength measurements (Özdemir et al, 2018). Different testing methods exert their effect due to difference in mechanisms and directions of force application during testing to the bonding interface between denture liner and the denture base (Özdemir et al, 2018). A case in point, it is generally accepted that peel bond strength of same materials during testing is approximately 1/10th less than their measured tensile strength (Maeda et al, 2012).

Test of bond strength between hard liners and denture base is more commonly tested by 3-point bending tests (Takahashi et al, 2001).

Resilient liners have been tested for bond strength with both tensile and shear bond strength testing with shear testing thought to be more clinically representative (Takahashi et al, 2001). Peel bond strength tests and shear bond strength tests are considered difficult to interpret (Chladek et al, 2014). Tensile test was concluded to be the most commonly preferred test in a systematic review of 57 included studies (Özdemir et al, 2018).

Wright et al (1982) described a peel test to measure the force needed to peel the lining material from a rigid denture base. This methodology was used by Sinobad et al (1992) in their bond strength study and a peel angle of 180° was used. Since peel test leads to stress concentration at the edges of the liner joint it is considered more clinically representative of the failure mode of soft reline materials in use (Demir et al, 2011).

For in-vitro testing of resilient liners, aging methods like water immersion and/ or thermocycling have been advocated (Chen et al, 2021). Water immersion aging will cause hydrolysis of bonding interface, while thermocycling aging will cause thermal stresses due to temperature changes. These aging methods will help create long term stresses that may be applied to the bonding interface between denture base and lining materials during its clinical use (Chen et al, 2021). It has been calculated 10000 cycles during thermocycling test will equate approximately 3 years' worth of clinical use of tested resilient liner (Maeda et al, 2012).

Thermocycling, interestingly, may lead to an increase in peel bond strength of direct chair-side plasticized acrylic-based resilient denture liners. This can be attributed to effect of heat applications during testing leading to enhanced polymerization of direct chair-side ABLTDL materials (Maeda et al, 2012). Conversely, it was concluded in another study that thermal cycling resulted in an overall weakening effect on the bond strength values of HTV SBLTDL bonded with different denture bases (Tugut et al, 2016). It can thus be safely concluded that adhesive strength of most of the long-term lining materials may decrease with water immersion or thermocycling and this is dependent on liner's chemical composition (Chladek et al, 2014).

5(g). Staining of resilient denture liners

Staining of long-term soft denture liners is a common problem encountered and could be a result of their porous nature as well (Chladek et al, 2014). Smoking was found to be the biggest culprit with approximately 50% of denture liner cases presenting with malodour and staining (Wright et al, 1984).

6. Disadvantages of resilient denture lining materials

Most of the commonly listed disadvantages to any denture soft reline materials include poor colour stability, lack of long-term dimensional stability, resilience or abrasion resistance, porosities, microbial adhesion, and weak bond strengths (Özdemir et al, 2018). Residual tastes, malodours, difficulty to clean, and water uptake are also considered to be some of the other disadvantages of resilient denture lining materials (Kreve et al, 2019). Loss of plasticizers, increased surface roughness, propensity for plaque formation, are some of the more commonly suggested drawbacks of soft denture liners in a recent systematic review (Muddugangadhar et al, 2020).

7. Process of relining

A thorough understanding of patient complaints and deficiencies of existing dentures is critical and need to be identified during comprehensive examination (Bowman et al, 1977). Thus, it has been correctly stated that reline procedures need to be based on an objective clinical criterion (Jumbelic et al, 1984). Only an adequate exiting CRDP should be considered for reline and a poorly designed and fabricated denture should ideally be remade (Hawkins et al, 1948).

Tissues which are supporting the denture must be healthy before they can be permanently relined (Lytle et al, 1957, Bowman et al, 1977, Jumbelic et al, 1984). Use of a tissue conditioner to first get denture supporting tissues back to health is recommended and only then dentures should be relined (Murata et al, 2008). Alternately, leaving CRDP out of mouth for at least 24-hours prior to denture relining procedures is also acceptable and has been recommended (Nassif et al, 1984).

To effectively soft reline an existing denture one must start with a CRDP that is stable, in good occlusion and well made (Murata et al, 2008, Hawkins et al, 1948). Some of the common mistakes to be avoided during relining procedures include losing control over vertical dimension of occlusion or 3D orientation of the denture, forward movement of dentures and introduction of occlusal discrepancies (Bowman et al, 1977).

Preliminary treatment before denture reline may need to be undertaken to achieve following objectives: re-establishing height, orientation, and esthetics of occlusal plane; re-establish correct esthetic position of maxillary denture and finally to relate maxillary and mandibular dentures in centric relation again (Zarb et al, 2013).

An appropriate surface treatment protocol can be used for the denture base that needs to be relined and the resilient liner material being employed (Özdemir et al, 2018). After adequate and even intaglio surface and peripheral border reduction an appropriate impression technique needs to be considered (Cagna et al, 2009). Both open mouth and closed mouth impression techniques can be effectively utilized to attain good clinical results with the chosen reline material (Bowman et al, 1977). When position of maxillary CRDP is acceptable, then maxillary denture can act as an impression tray utilizing its relationship with hard palate as reference for repeatable consistent seating during reline procedures. When extensive changes to VDO need to be made or orientation of the maxillary denture needs to be corrected during reline procedure, it may be advisable to utilize tissue stops (Zarb et al, 2013). A study described the technique to achieve this corrected positioning of maxillary denture using VPS border moulding material, leading to repeatable and consistent denture placement while relining impression procedures are undertaken (Cagna et al, 2009).

A clinical remount of relined CRDP on an articulator after processing is critical and often needed for occlusal corrections and patient comfort during function (Nassif et al, 1984).

It has been suggested that relining an existing denture is a very complicated procedure which requires astute clinical judgement and precise skills with immaculate execution (Bowman et al 1977).

8. Maintenance of soft relined dentures

A soft toothbrush with soap is recommended or just rinsing and wiping the resilient liner with a wet cotton pad is also acceptable (Zarb et al, 2013). Brushing with toothpaste and a brush can increase surface roughness thus it is recommended that chemical methods of cleaning are first choice for any resilient denture liner (Kreve et al, 2019). But it should be kept in mind that even with most careful chemical disinfection protocols, over time, there is an expected increase in surface roughness of various resilient liners (Machado et al, 2009).

9. Resilient liner selection

There is a huge conundrum when selecting a resilient liner for your denture case. Questions come to mind, should you use a silicone or more viscoelastic plasticized acrylic. Ideally speaking a material with permanent resiliency and compliance of a silicone-based denture lining material but bond strengths of a plasticized acrylic-base denture lining material may be best for clinical use (Wright et al, 1976). For patients with extremely poor ridge and thin friable tissues it has been advised to use a softer more compliant denture liner. While patients requiring relief during masticatory function or due to parafunctional habits; may benefit from a more resilient liner (Pesun et al, 2019). Generally speaking, when encountered with a patient requiring soft denture liners, it may be advisable to start with a silicone liner for durability and if patient is not satisfied that they can be switched to plasticized acrylics (Murata et al, 2008).

Soft denture liners are employed in almost 5% of new CRDPs fabricated and thus, will have a continuous important role in satisfactory denture service (Mack et al, 1989). Ideal material selection for the case encountered, is the key to effective use of soft denture liners (Murata et al, 2008).

Kubo et al (2014) said it best while concluding their review on relining of CRDPs. To obtain satisfactory result with relining procedures it is critical that a clinician understands their indications, contraindications, advantages, and disadvantages and have an intricate knowledge and insight into their material properties and characteristics (Kubo et al, 2014).

The procedure of relining CRDPs can be considered more difficult to accomplish successfully as compared to any single procedure undertaken during denture fabrication appointments (Jumbelic et al, 1984). Moreover, since residual ridge resorption is a continuous lifelong process even long - term relining procedures only provide a temporary solution (Chai et al, 1998). Complexities of the relining procedure and short comings of the liner materials encountered; lead Bowman et al (1977) to conclude that often times remake of an ill-fitting CRDP may be advisable over a complex relining procedure.

1.3 Statement of problem

More and more complete removable dentures are being fabricated utilizing CAD/CAM technologies due to their ease of fabrication, potential cost effectiveness and unarguably better physical properties. Continued residual ridge resorption makes maintenance of close denture base adaptation to the underlying tissues a challenge. Resilient denture liners with their multiple advantages and indications will keep on being utilized in removable prosthodontics. Thus, testing of the bonding interactions of these materials is a relevant topic for today's prosthodontic researcher.

To my knowledge there is currently no research on peel bond strength measurements to evaluate adhesive behaviour of resilient liners on modern CAD/CAM dentures.

1.4 Purpose of this study

The aim of this study is to determine the peel bond strengths between plasticized acrylic resin-based long-term denture liner, silicone-based long-term denture liner, and tissue conditioner and CAD/CAM denture bases (subtractive and additive) and compare them to peel bond strength between these soft reline materials and conventionally manufactured PMMA denture base. A secondary aim of this study is to determine effects of 10-day water immersion on peel bond strength of these materials.

1.5 Objective of this study

- Evaluate peel bond strengths of plasticized acrylic-based long-term denture liners bonded to conventional, subtractive, and additive denture bases.
- Evaluate peel bond strengths of silicone-based long-term denture liners bonded to conventional, subtractive, and additive denture bases.
- Evaluate if peel bond strengths differ between plasticized acrylic-based long-term denture liners and silicone-based long-term denture liners.
- Evaluate if type of denture base affects the peel bond strengths of either plasticized acrylic-based or silicone-based long term denture liners.

- Evaluate if water immersion has any effect on the peel bond strengths of plasticized acrylic-based and silicone-based long-term denture liners bonded to conventional, subtractive, and additive denture bases.
- Evaluate peel bond strengths of tissue conditioner bonded to conventional, subtractive, and additive denture bases.
- Evaluate if type of denture base affects the peel bond strengths of tissue conditioner.
- Evaluate if water immersion has any effect on the peel bond strengths of tissue conditioner bonded to conventional, subtractive, and additive denture bases.

1.6 Null Hypothesis

H01: Plasticized acrylic-based long term denture liner materials will not be different in terms of peel bond strength from silicone-based long-term denture liner materials in relation to conventional, additive, and subtractive manufactured denture bases.

H02: Manufacturing method of denture base resin will have no effect on peel bond strength of plasticized acrylic-based denture-liner materials, silicone-based denture-liner materials, or tissue conditioner material.

H03: Water immersion will have no effect on durability of peel bond strength.

Chapter 2

Methods and Methodology

This study design and methodology has been adapted from previously designed and used methodologies in various studies testing on peel bond strength of resilient liners as described by Maeda et al, 2012, Tanimoto et al, 2012, Alcantara et al, 2012 and Choi et al, 2018. Figure 5. depicts my methodology for this study in a flow chart form.

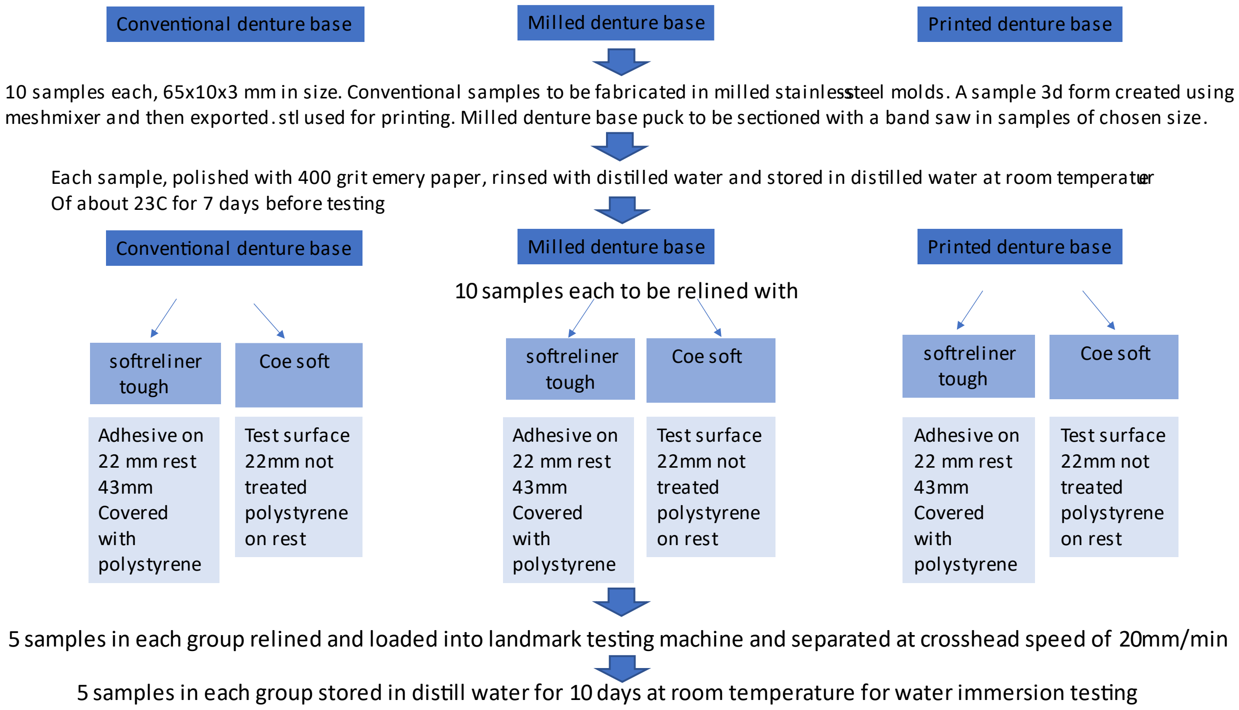


Figure 5. Research methodology flowchart

In this in-vitro study, peel bond strength of three different commercially available denture bases (conventional press and packed, subtractive, and additive) to two different long-term resilient denture liner materials (plasticized acrylic-based long-term denture liner and silicone-based long-term denture liner); were evaluated. In second part of this study, peel bond strength of all three denture bases relined with a tissue conditioner was tested. Finally, effects of 10-days of water immersion on peel bond strengths of different denture bases and liner materials were also evaluated.

2.1 Materials

TYPE	TECHQUINE	NAME	MANUFACTURER	LOT NUMBER
Conventional Denture Base	Pressure packed and heat cured	ProBase Hot Polymer/Monomer	Ivoclar Vivadent, Schaan, Liechtenstein	YB1VHX Z01H18
Milled Denture Base	Subtractive	IvoBase CAD	Ivoclar Vivadent, Schaan, Liechtenstein	YB3KF9
Printed Denture Base	Additive	FormLabs Denture Base RP	DENTCA Inc, Torrance, CA, USA	BF19J21R
Silicone liner	Silicone elastomer, auto-polymerizing	SofReliner Tough Soft	Tokuyama Dental Co, Toyko, Japan	235E71
Soft acrylic liner	Plasticized acrylic, auto-polymerizing	Coe-Soft	GC labs, Alsip, USA	2109141
Tissue conditioner	Plasticized acrylic, auto-polymerizing	Coe-Comfort	GC labs, Alsip, USA	2101251

Table 4. Materials used in this study

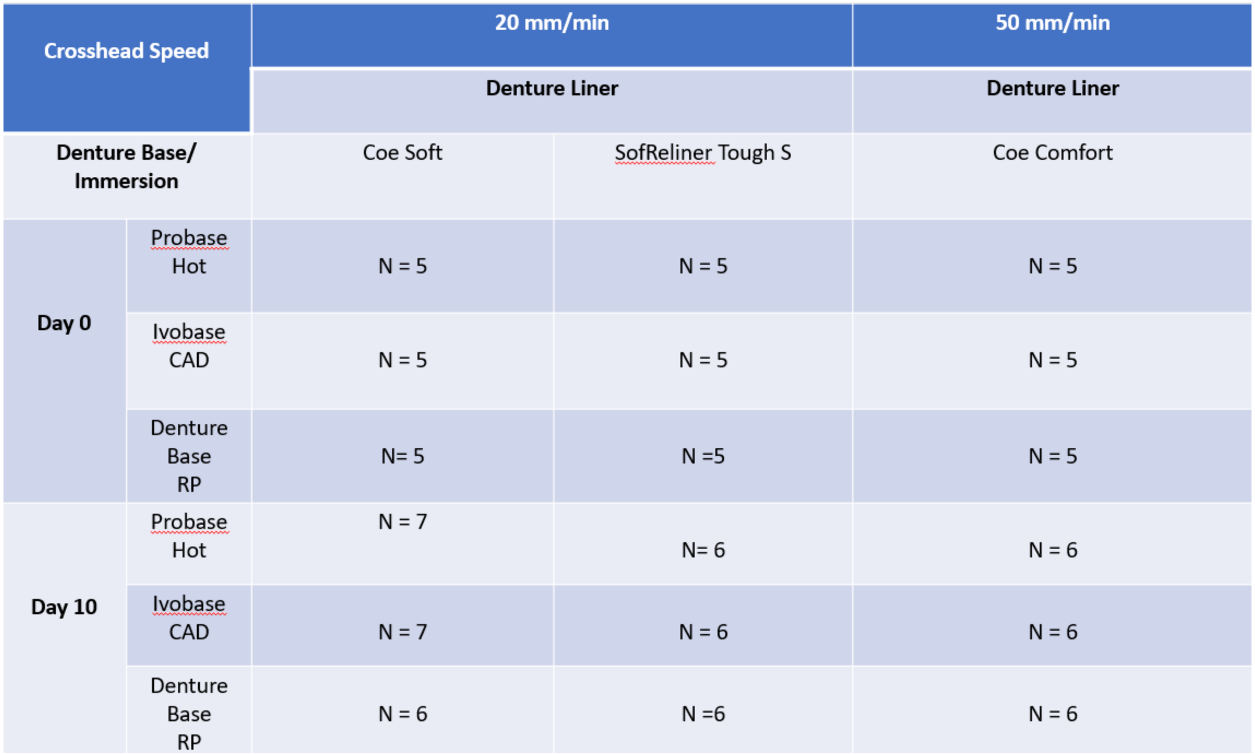
Denture base materials that were used in this study included: 1. conventional heat cured PMMA was ProBase Hot (Lot No. Powder- YB1VHX, Liquid- Z01H18; Ivoclar Vivadent, Schaan, Liechtenstein); 2. prepolymerized PMMA pucks were IvoBase CAD (Lot No. YB3KF9; Ivoclar Vivadent, Schaan, Liechtenstein); 3. photopolymerizable denture base resin was Denture base RP (Lot No. BF19J21R; DENTCA Inc., Torrance, CA, USA).

Resilient liners that were used in this study included: 1. RTV silicone-based long-term denture lining material was Sofreliner Tough S (Lot No. 235E71; Tokuyama Dental Co, Tokyo, Japan); 2. autopolymerizing plasticized acrylic-based long-term denture liner Coe Soft (Lot No. 2109141; GC labs, Alsip, USA).

Tissue conditioner that was tested in this study was Coe Comfort (Lot No. 2101251; GC labs, Alsip, USA).

2.2 Experimental Groups

A total of 90 denture base samples were created for this study, 30 samples per each class of denture reline material (plasticized acrylic-based long-term denture liner, silicone-based long-term denture liner, and tissue conditioner). Power calculations were based on another referenced study evaluating adhesive strength of resilient denture liners to different denture bases (Choi et al, 2018). Samples were then divided into their respective test groups as shown in Table 5.



Crosshead Speed		20 mm/min		50 mm/min
		Denture Liner		Denture Liner
Denture Base/ Immersion		Coe Soft	SofReliner Tough S	Coe Comfort
Day 0	Probase Hot	N = 5	N = 5	N = 5
	Ivobase CAD	N = 5	N = 5	N = 5
	Denture Base RP	N= 5	N =5	N = 5
Day 10	Probase Hot	N = 7	N= 6	N = 6
	Ivobase CAD	N = 7	N = 6	N = 6
	Denture Base RP	N = 6	N =6	N = 6

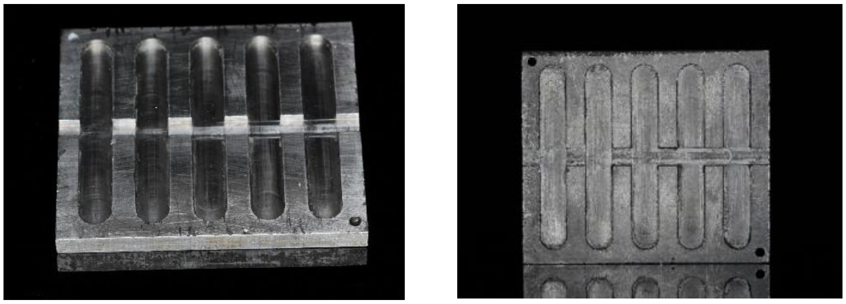
Table 5. Experimental setup with respective test groups

In each denture base groups sample numbers 1-5 were relined and then tested for peel bond strengths. Sample numbers 6-10 were relined and then subjected to aging by immersion in distilled water for 10-days at room temperature. Additional samples (n=1 or 2) were added in 10-day immersion group to ensure we had extras in case of any outliers as a result of aging process.

2.3 Preparation of Samples

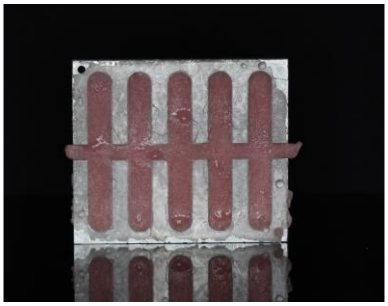
Denture base acrylic samples were fabricated using conventional heat cured PMMA (ProBase Hot; Lot No. Powder- YB1VHX, Liquid- Z01H18; Ivoclar Vivadent, Schaan, Liechtenstein). For conventional heat processing of acrylic denture base samples, we used stainless steel moulds (with slots that had inner dimensions of 65 X 10 X 3 mm); that were previously fabricated for another denture reline study. Heat cured PMMA was polymerized according to manufacturer's instructions to create rectangular acrylic blocks of 65 X10 X 3 mm. ProBase Hot powder and liquid was measured in manufacturer recommended ratios and properly mixed. Probase Hot mix was packed in doughy stage into stainless-steel moulds under compression using manufacturer recommended "trial packing" method and processed overnight in a water bath. Moulds were allowed to bench cool before deflasking was undertaken. Probase Hot denture base samples needed to be sectioned to separate them into individual samples using 0.3 mm sectioning discs (Komet USA LLC, Rock Hill, SC, USA). Any sharp edges if present were smoothened with fine carbide long shank lab burs.

a.



b.

c.



d.

Figure 6. a. ProBase Hot, b. Stainless steel moulds used for sample fabrication, c. C Clamp used to maintain pressure during polymerization, d. Polymerized acrylic denture base samples in mould before seperation.

Subtractive CAD/ CAM denture base samples were created using prepolymerized PMMA pucks (IvoBase CAD; Lot No. YB3KF9; Ivoclar Vivadent, Schaan, Liechtenstein). The CAD/CAM specimens were prepared by cutting pucks into test sample dimensions (65 X10 X3mm) utilizing band saws. The external two layers from either side of the puck were discarded after sectioning to ensure that all the test samples had similar surface texture created by the band saw before surface preparation for testing.

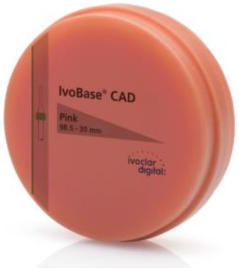


Figure 7. IvoBase CAD puck

For additive CAD/CAM denture base samples, first a prototype sample in dimensions of 65 X10 X 3mm was designed using a free CAD software program (Meshmixer, Autodesk, Mill Valley, California, USA) and exported as standard tessellation language (STL) data set. This STL was exported to the PreForm software (Formlabs Inc., Somerville, MA, USA) so that, print orientation and layout could be finalized and supports could be generated for optimized printing. 3D printing was performed with a Form 3B printer (Formlabs Inc., Somerville, MA, USA); using a photopolymerizable denture base resin containing aliphatic urethane dimethacrylate (Denture base RP; Lot No. BF19J21R; DENTCA Inc., Torrance, CA, USA). We utilized a print orientation of 90° with a layer thickness set at 50 µm. After printing, proper post processing was completed following manufacturer’s recommendations. First denture base samples were washed for 20 mins in 99 % concentration IPA using a Form Wash unit (Formlabs Inc., Somerville, MA, USA). After allowing the washed samples to air dry, printed denture base samples were next cured using a Form Cure unit (Formlabs Inc., Somerville, MA, USA). As per manufacturer’s instructions, first glycerin was preheated in a glass jar to 80° C in the Form Cure unit. Air dried samples were next fully submerged in the glycerin inside the Form Cure. These were first cured for 30 minutes at 80° C and then after flipping the opposite side, it was cured again at 80° C for another 30 minutes. Post-cured samples were washed with soap and denture brush to get rid of glycerin and supports were removed using 0.3 mm sectioning discs (Komet USA LLC, Rock Hill, SC, USA). Any sharp edges if present were smoothened with fine carbide long shank lab burs.

Figure 8. a. Form 3B printer, b. Form Wash and Form Cure, c. Denture Base resin, d. Printed samples on the print plate, e. Samples in glycerin jar for post curing, f. Cured sample before support was removed

After fabrication, all the samples, before they received reline materials, were subjected to some surface preparation following protocols employed by Maeda et al, (2012), Alcantara et al, (2012). Aim of this surface preparation was to achieve similar clean surfaces for each sample of denture base material, devoid of any separating media, uncured resin, glycerin, or any other contaminants. This was achieved by scrubbing the denture base samples first with 1200 grit sandpaper discs and finally polishing with 400 grit emery paper (Norton Abrasives, Worcester, MA, USA). To standardize the samples, similar length of emery paper was used. As we lack an electric polisher, efforts were made to utilize same number of manual strokes of similar intensity to polish the samples.

After preparation, abraded surfaces were cleaned to remove any debris using protocols described by Alcantara et al (2012). All samples were first scrubbed with soap and a denture brush and then rinsed under running tap water for 20 seconds. Finally, these samples were additionally cleaned in an ultrasonic bath with distilled water for 20 minutes. Based on availability of the laboratory time for testing, these prepared denture samples were stored in distilled water at room temperature for 7-days before relining procedures were undertaken.

Once we were ready for relining procedure to be undertaken, all the prepared samples were allowed to air dry for at least 5 minutes at room temperature.

Based on included reference studies for methodology, it was decided that only one-third length (approximately 22 mm) of the test sample would be bonded to denture base and two-third length (approximately 43 mm) would be left non- bonded. This was done to generate a peeling force during testing at the bonding interface. A blue pencil mark was drawn on prepared surface of all the samples to help envision demarcation between bonded and non-bonded lengths of the denture base samples.

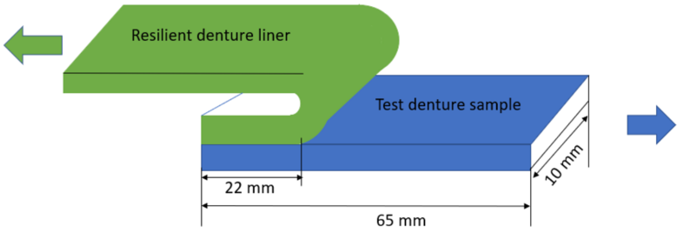


Figure 9. Diagrammatic representation of the test sample {adapted from Maeda et al, 2010}

For samples receiving silicone-based long-term denture liner, a compatible bonding agent that is supplied by the manufacturer along with the Sofreliner Tough S kit was utilized (Sofreliner Tough S, Lot No. 235E71; Tokuyama Dental Co, Tokyo, Japan). Adhesive was applied to only the 22 mm length of the test sample that was to be bonded and allowed to air dry for 15 minutes. Every effort was made to limit the spread of silicone adhesive and confine it to the areas being bonded only. For samples receiving plasticized acrylic-based long-term denture liner and tissue conditioner, no other special surface treatments that may enhance bonding were performed to the prepared surface. This was decided to allow plasticized acrylic-based long-term denture liner and tissue conditioner to bond with the denture base because of their innate bonding capability only.

Non-bonded areas on all the samples were carefully coated with a very thin layer of lubricant supplied by the manufacturer, along with the Coe Soft resilient liner kit (Coe Soft, Lot No. 2109141; GC labs, Alsip, USA) and allowed to air dry. Additionally, it was decided to also cover the non bonded area with polystyrene strips, again supplied by the manufacturer along with Coe Soft resilient liner kit (Coe-Soft Lot No. 2109141; GC labs, Alsip, USA). Both these measures were expected to prevent bonding of the Coe Soft and Coe Comfort to the areas that were to be left non-bonded as required by the peel testing set-up.

For standardization, the previously used stainless steel moulds were again employed in relining procedure. Again, blue pencil marks were drawn on the mould itself to denote 22mm that would be bonded. For silicone reline material, Sofreliner Tough S was injected into each slot in the stainless-steel mould, the area to be non-bonded was identified by previously drawn pencil mark on the mould and then reline material in this non-bonded region of the mould was covered with a polystyrene strip. Test sample was inverted carefully on to each slot with prepared surface towards the liner material ensuring only adhesive applied bonding area was allowed to be in contact with the liner and lubricated surface was ensured to be in contact with the polystyrene strip. A glass slab of approximately 500mg in weight was placed on this assembly and held in place with light finger pressure for 5 minutes. This was done to stimulate light intra-oral pressure that patients are instructed to use clinically during closed mouth direct chair-side reline procedures.

For plasticized acrylic-base long-term denture liner resin, properly measured powder and liquid were carefully mixed following manufacturer’s instructions. Next each slot in the stainless-steel mould was filled with the reline material and then same steps as silicone liner were followed to create Coe Soft lined test samples. Coe comfort lined samples were also created following similar steps as Coe Soft lined test samples.

After separation from the moulds, overlying excess liner material was trimmed with sharp knives and blades to match the underlying denture samples. This was done to ensure that all the test samples had a uniform unstretched length and width of the liner material before stretch test was initiated.

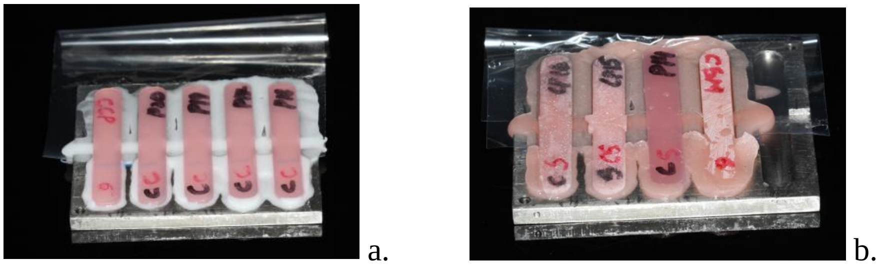
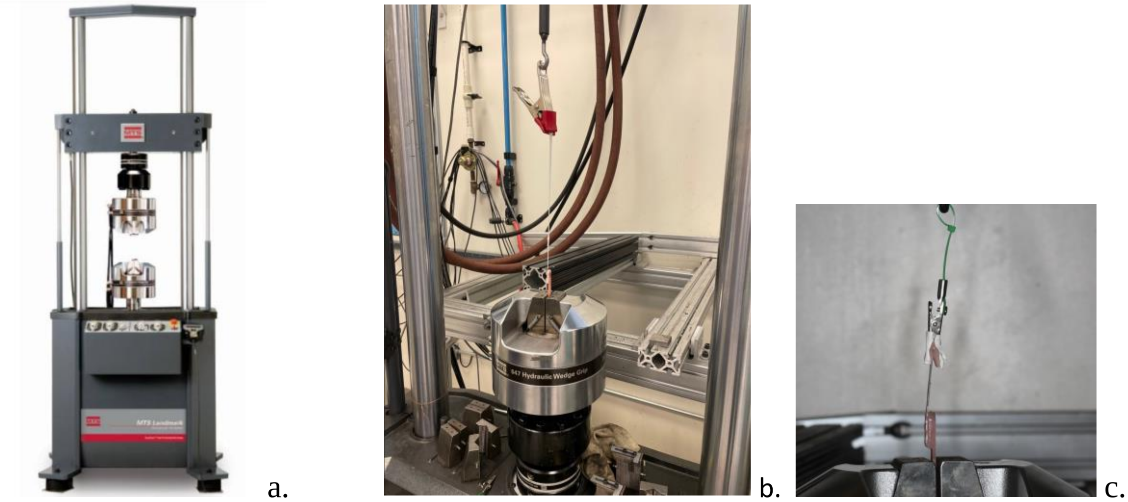

a. b.

Figure 10. Reline assembly in the mould with polystyrene strip a. Denture Base RP samples lined with Coe Comfort, b. ProBase Hot samples lined with Coe Soft

2.3 Peel test

Peel bond strength between denture base samples and chosen resilient liners and tissue conditioner was tested on a Landmark® Servohydraulic Test System (MTS Systems, Eden Prairie, MN, USA). Figure 11 shows images of the test specimens loaded into the testing machine.


a. b. c.

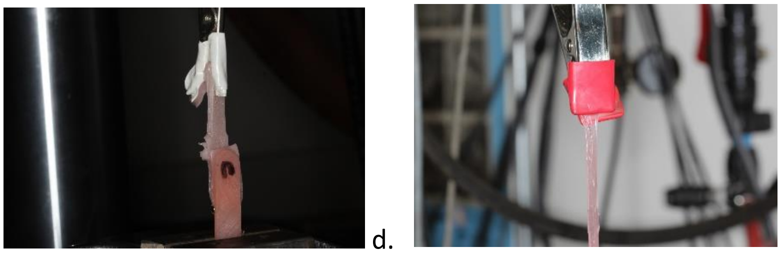

d. e.

Figure 11. Test specimens in the testing machine a. Landmark® Servohydraulic Test System, b and e. Relined sample testing using a clamp to hold liner material, c and d. Relined sample testing using an electric alligator clip to hold tissue conditioner material

In each denture base groups sample numbers 1-5 were tested for peel bond strengths same day after relining procedures were undertaken. Sample numbers 6-10 were relined and then subjected to aging by immersion in distilled water for 10 days at room temperature as an adaptation of methodology previously described by Alcantara et al (2012).

After loading into the testing machine, Tokuyama Sofreliner Tough S and Coe Soft lined samples were tested at room temperature at cross head speeds of 20 mm/min till failure occured. Whereas, Coe Comfort lined samples were tested at cross head speeds of 50 mm/min till failure occurred.

2.4 Failure Analysis

After testing each sample was removed from the machine and was carefully inspected with the naked eye and visually analysed for nature of bond . Based on these visual observation of the bond failure, modes of debonding were classified as adhesive, cohesive or mixed.

Adhesive failure in this study refers to total seperation at the bonding interface.

Cohesive failure is the tearing of the resilient liner while mixed failure referrs to both adhesive and cohesive type of failures.

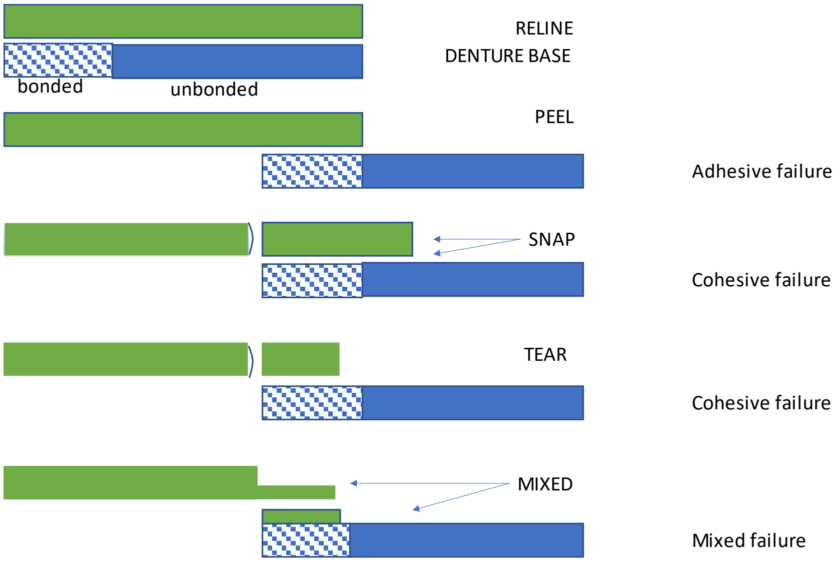


Figure 12. Classification of liner failures

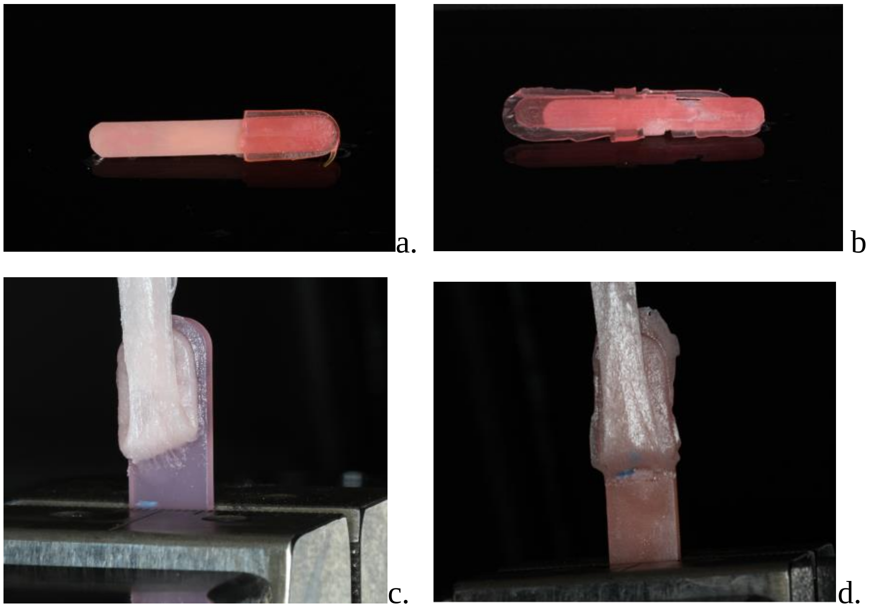


Figure 13. Liner failures a. Cohesive (Snap kind), b. Mixed, c. Reline material starting to peel, d. Reline material stretching without much peeling.

2.5 Data collected

Load (N) at which failure occured was recorded, similarly stretched length of the liner at the time of failure was measured using an electric ruler. These measurements were then converted into peel bond strength using formula described by Maeda et al (2012).

$$Ps = F \times W^{-1} \left[\frac{1 + (1 + E)}{2} \right]$$

Here F is applied force at which failure occurred, W is the width of specimen in peeling area, E is the extension ratio of material (ratio of stretched to unstretched lengths of the liner material).

2.6 Data Analysis

3 way Analysis of Variance testing (ANOVA) was performed to determine whether statistical differences exist between materials and water immersion for the main study utilizing Tokuyama Sofreliner Tough S and Coe Soft. On the other hand for the second part of the study using Coe Comfort a 2 way Analysis of Variance testing (ANOVA) was performed to determine whether statistical differences exist between denture base material and due to water immersion. A Tukey Test was used to determine if relationship between data sets was statistically significant. Also a Levene’s test was performed to assess the equality of variances. All data was analyzed at a 0.05 level of significance using OriginLab (v. 2019b; OriginLab Corp, MA, USA).

Chapter 3

Results

3.1 Main study

For the main study evaluating peel bond strength of Sofreliner Tough S and Coe Soft with the 3 different denture bases, mean and standard deviation values at 0-days and after 10-days of water immersion are presented in a graphic form in Figure 14. All the descriptive statistics along with mean comparisons are shown in Figure 15 and graphically represented in Figure 16.

Results of 3-way ANOVA test show, that type of denture base (P value = 0.5274 at confidence level of 0.05) and the 10-day water storage (P value = 0.58073 at confidence level of 0.05); had no significant effect on the peel bond strength values.

Whereas the type of reline material (P value = 0 at confidence level of 0.05), did significantly affect the peel bond strength.

Interactions between reline material and storage (P value = 0.4118 at confidence level of 0.05) were not statistically significant. Interactions between reline material and denture base (P value = 3.98459E-6 at confidence level of 0.05); denture base and storage (P value = 0.02159 at confidence level of 0.05) and reline material, denture base and storage (P value = 0.00354 at confidence level of 0.05); were all statistically significant.

Results show that overall peel bond strength values were significantly higher for Tokuyama Sofreliner Tough S (Mean 1.6452 ± 0.17669 MPa) as compared to Coe Soft (Mean 0.20005 ± 0.10727 MPa); irrespective of denture base type or 10-day water storage.

Results show that, overall peel bond strength values of Coe Soft were highest for Formlabs Denture Base RP (Mean 0.25678 ± 0.077 MPa), followed by IvoBase CAD (Mean 0.24682 ±0.10118 MPa), and lowest for ProBase Hot (Mean 0.10127 ± 0.06077 MPa). These differences were statistically significant.

Overall peel bond strength values for Tokuyama Sofreliner Tough S were highest with ProBase Hot (Mean 1.75187 ± 0.19223 MPa), followed by Formlabs Denture Base RP (Mean 1.62783 ±

0.14758 MPa), and lowest for IvoBase CAD (Mean 1.55589 ± 0.1398 MPa). These differences were statistically significant.

Results show that there is may be a trend for reduction of peel bond strength values with 10-day water immersion for Coe Soft while Sofreliner Tough S was not affected.

Overall peel bond strength for Coe Soft lined samples at 0 days (Mean 0.22546 ± 0.09066 MPa) reduced after 10-days of water immersion (Mean 0.18099 ± 0.11681 MPa); these differences were not statically significant.

Overall peel bond for Tokuyama Sofreline Tough S lined samples at 0-days (Mean 1.6411 ± 0.25288 MPa) was similar after 10-days of water immersion (Mean 1.64861 ± 0.07795 MPa); these differences were not statistically significant.

Results showed significant interactions between reline materials, denture base and storage (P value = 0.00354 at confidence level of 0.05). Overall, there was a generalised trend for reduction of peel bond strength values with 10-day water immersion except in Coe Soft on Formlabs Denture Base RP where peel bond strength increased at 10-days (Mean 0.31121 ± 0.02352 MPa) from 0-days (Mean 0.19145 ± 0.06596). Similarly, Sofreliner tough S lined samples of IvoBase CAD showed increase in peel bond strength values at 10-days (Mean 1.6347 ± 0.04719 MPa) as compared to 0-days (Mean 1.46131 ± 0.15993 MPa). All these changes in peel bond strength values were found to be statistically significant.

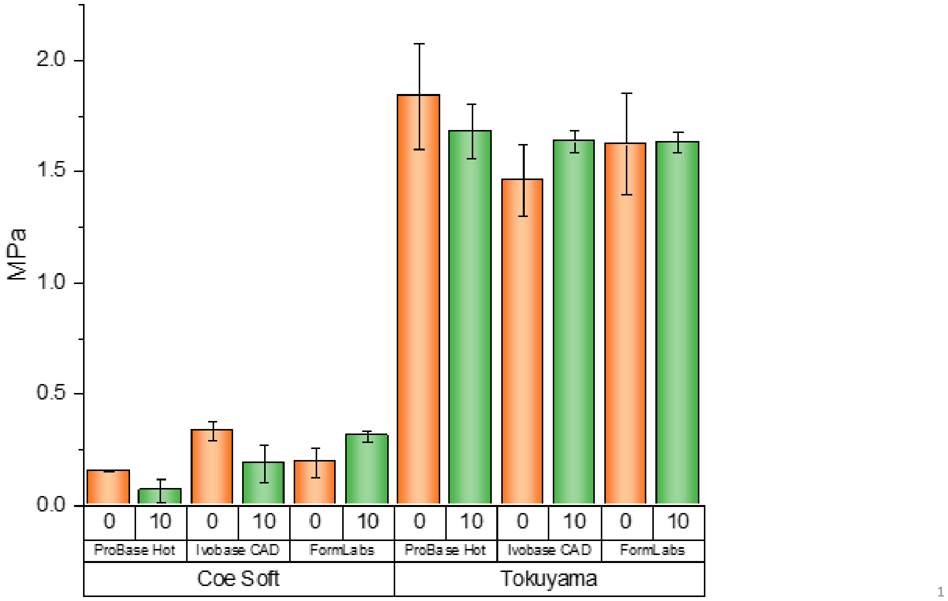
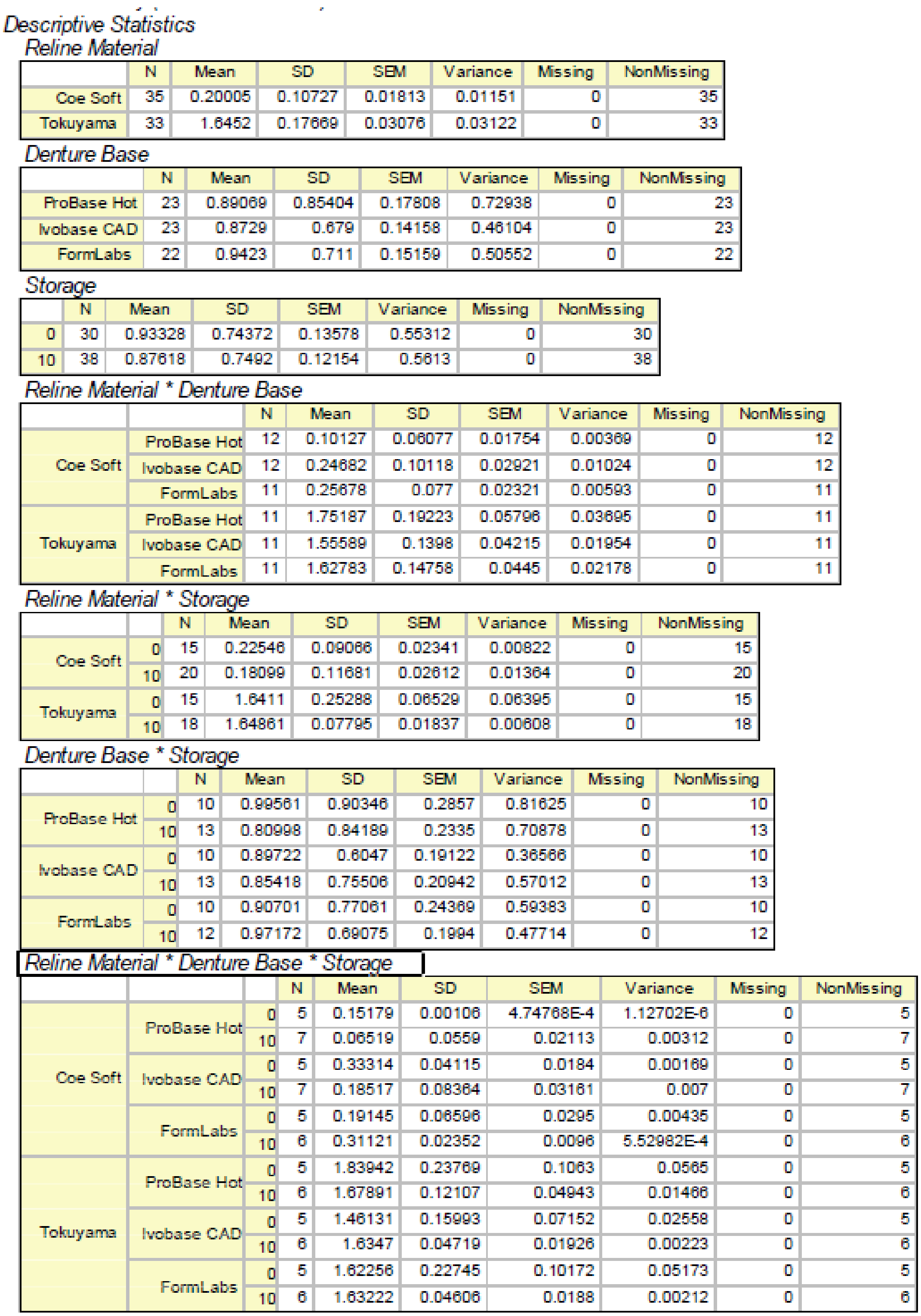


Figure 14. Graphical Representation of Mean and Standard Deviation for Peel Bond Strength Values of Each Coe Soft and Sofreliner Tough S with different Denture Bases at 0-days and 10-days



Descriptive Statistics

Reline Material

	N	Mean	SD	SEM	Variance	Missing	NonMissing
Coe Soft	35	0.20005	0.10727	0.01813	0.01151	0	35
Tokuyama	33	1.6452	0.17669	0.03076	0.03122	0	33

Denture Base

	N	Mean	SD	SEM	Variance	Missing	NonMissing
ProBase Hot	23	0.89069	0.85404	0.17808	0.72938	0	23
Ivobase CAD	23	0.8729	0.679	0.14158	0.46104	0	23
FormLabs	22	0.9423	0.711	0.15159	0.50552	0	22

Storage

	N	Mean	SD	SEM	Variance	Missing	NonMissing
0	30	0.93328	0.74372	0.13578	0.55312	0	30
10	38	0.87618	0.7492	0.12154	0.5613	0	38

Reline Material * Denture Base

		N	Mean	SD	SEM	Variance	Missing	NonMissing
Coe Soft	ProBase Hot	12	0.10127	0.06077	0.01754	0.00369	0	12
	Ivobase CAD	12	0.24682	0.10118	0.02921	0.01024	0	12
	FormLabs	11	0.25678	0.077	0.02321	0.00593	0	11
Tokuyama	ProBase Hot	11	1.75187	0.19223	0.05796	0.03695	0	11
	Ivobase CAD	11	1.55589	0.1398	0.04215	0.01954	0	11
	FormLabs	11	1.62783	0.14758	0.0445	0.02178	0	11

Reline Material * Storage

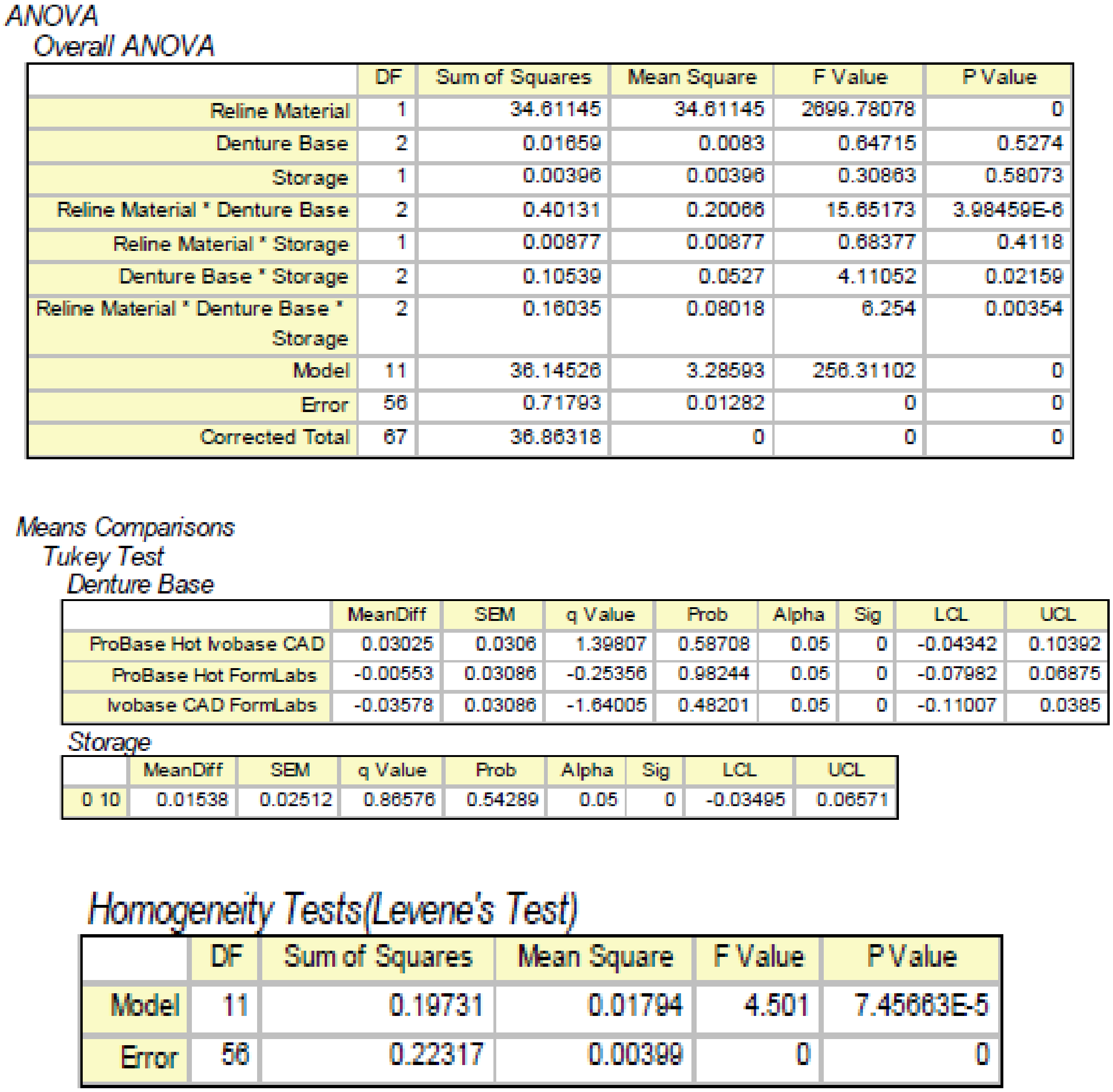
		N	Mean	SD	SEM	Variance	Missing	NonMissing
Coe Soft	0	15	0.22546	0.09066	0.02341	0.00822	0	15
	10	20	0.18099	0.11681	0.02612	0.01364	0	20
Tokuyama	0	15	1.6411	0.25288	0.06529	0.06395	0	15
	10	18	1.64861	0.07795	0.01837	0.00608	0	18

Denture Base * Storage

		N	Mean	SD	SEM	Variance	Missing	NonMissing
ProBase Hot	0	10	0.99561	0.90346	0.2857	0.81625	0	10
	10	13	0.80998	0.84189	0.2335	0.70878	0	13
Ivobase CAD	0	10	0.89722	0.6047	0.19122	0.36566	0	10
	10	13	0.85418	0.75506	0.20942	0.57012	0	13
FormLabs	0	10	0.90701	0.77061	0.24369	0.59383	0	10
	10	12	0.97172	0.69075	0.1994	0.47714	0	12

Reline Material * Denture Base * Storage

			N	Mean	SD	SEM	Variance	Missing	NonMissing
Coe Soft	ProBase Hot	0	5	0.15179	0.00106	4.74768E-4	1.12702E-6	0	5
		10	7	0.06519	0.0559	0.02113	0.00312	0	7
	Ivobase CAD	0	5	0.33314	0.04115	0.0184	0.00169	0	5
		10	7	0.18517	0.08364	0.03161	0.007	0	7
	FormLabs	0	5	0.19145	0.06596	0.0295	0.00435	0	5
		10	6	0.31121	0.02352	0.0096	5.52982E-4	0	6
Tokuyama	ProBase Hot	0	5	1.83942	0.23769	0.1063	0.0565	0	5
		10	6	1.67891	0.12107	0.04943	0.01466	0	6
	Ivobase CAD	0	5	1.46131	0.15993	0.07152	0.02558	0	5
		10	6	1.6347	0.04719	0.01926	0.00223	0	6
	FormLabs	0	5	1.62256	0.22745	0.10172	0.05173	0	5
		10	6	1.63222	0.04606	0.0188	0.00212	0	6



ANOVA

Overall ANOVA

	DF	Sum of Squares	Mean Square	F Value	P Value
Reline Material	1	34.61145	34.61145	2699.78078	0
Denture Base	2	0.01659	0.0083	0.64715	0.5274
Storage	1	0.00396	0.00396	0.30863	0.58073
Reline Material * Denture Base	2	0.40131	0.20066	15.65173	3.98459E-6
Reline Material * Storage	1	0.00877	0.00877	0.68377	0.4118
Denture Base * Storage	2	0.10539	0.0527	4.11052	0.02159
Reline Material * Denture Base * Storage	2	0.16035	0.08018	6.254	0.00354
Model	11	36.14526	3.28593	256.31102	0
Error	56	0.71793	0.01282	0	0
Corrected Total	67	36.86318	0	0	0

Means Comparisons

Tukey Test

Denture Base

	MeanDiff	SEM	q Value	Prob	Alpha	Sig	LCL	UCL
ProBase Hot Ivobase CAD	0.03025	0.0306	1.39807	0.58708	0.05	0	-0.04342	0.10392
ProBase Hot FormLabs	-0.00553	0.03086	-0.25356	0.98244	0.05	0	-0.07982	0.06875
Ivobase CAD FormLabs	-0.03578	0.03086	-1.64005	0.48201	0.05	0	-0.11007	0.0385

Storage

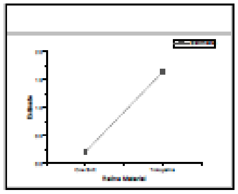
	MeanDiff	SEM	q Value	Prob	Alpha	Sig	LCL	UCL
0 10	0.01538	0.02512	0.86576	0.54289	0.05	0	-0.03495	0.06571

Homogeneity Tests(Levene's Test)

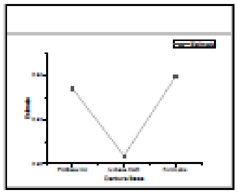
	DF	Sum of Squares	Mean Square	F Value	P Value
Model	11	0.19731	0.01794	4.501	7.45663E-5
Error	56	0.22317	0.00399	0	0

Figure 15. Descriptive statistics and the mean comparisons for Sofreliner Tough S and Coe Soft

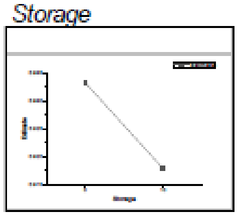
Reline Material



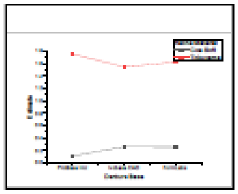
Denture Base



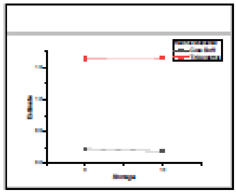
Storage



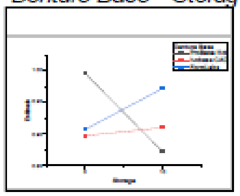
Reline Material * Dentur



Reline Material * Storag



Denture Base * Storag



Reline Material * Dentur

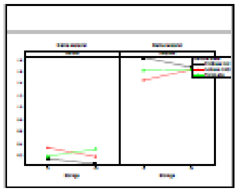


Figure 16. Graphic representation of 3-way ANOVA data

3.2 Tissue conditioner study

For the second part of this thesis evaluating peel bond strength of Coe Comfort with the 3 different denture bases, all the descriptive statistics along with mean and standard deviation value comparisons are shown in Figure 17 and graphically represented in Figure 18.

Results of 2-way ANOVA test show, that type of denture base (P value = 0.00728 at confidence level of 0.05) and the 10-day water storage (P value = 0.00278 at confidence level of 0.005); had significant effect on the peel bond strength values of Coe Comfort tissue. Similarly, interactions between denture base and water immersion also had statistically significant effect on peel bond strength of coe comfort (P value = 0.03352 at confidence level of 0.05).

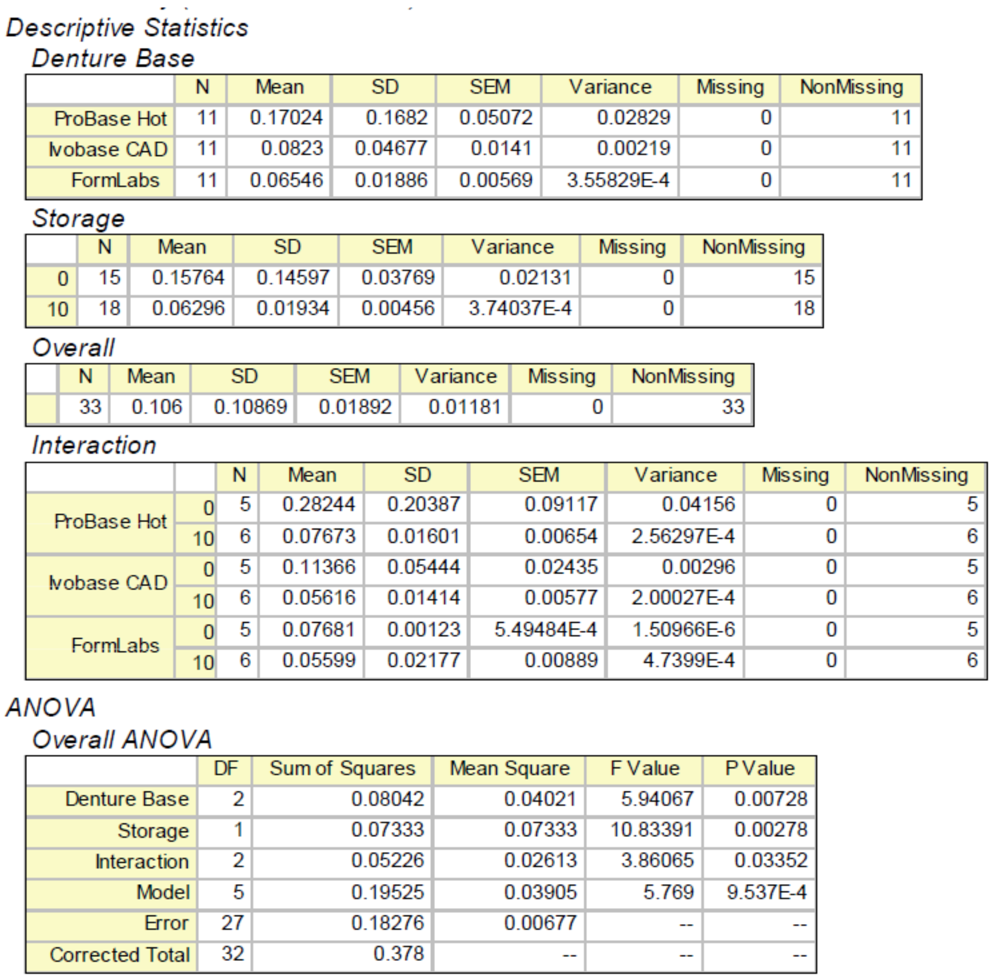
Overall, Coe Comfort showed highest peel bond strength with Probase Hot (Mean 0.17024 ± 0.1682 MPa), while Formlabs Denture Base RP showed lowest peel bond strength (Mean 0.06546 ± 0.01886 MPa). IvoBase CAD had intermediate mean peel strength (Mean 0.0823 ± 0.04677 MPa).

Results show that there is a generalised trend for reduction of peel bond strength values of Coe Comfort after 10-day water immersion with both ProBase Hot and IvoBase CAD denture base samples. Whereas this reduction in peel bond strength of Coe Comfort is smaller on Denture Base RP group.

For ProBase Hot, peel bond strength with Coe Comfort at 0-days (Mean 0.28244 ± 0.20387 MPa) reduced to (Mean 0.07673 ± 0.01601 MPa) after 10-days of water immersion, this change was statistically significant.

For IvoBase CAD, peel bond strength with Coe Comfort at 0-days (Mean 0.11366 ± 0.05444 MPa) reduced to (Mean 0.05616 ± 0.01414 MPa) after 10-days of water immersion. This reduction in peel bond strength was statistically significant.

For Formlabs Denture Base RP, peel bond strength with Coe Comfort at 0-days (Mean 0.07681 ± 0.00123 MPa) reduced to (Mean 0.05599 ± 0.02177 MPa) after 10-days of water immersion. These differences in peel bond strength values were found to be statistically significant.



Descriptive Statistics

Denture Base

	N	Mean	SD	SEM	Variance	Missing	NonMissing
ProBase Hot	11	0.17024	0.1682	0.05072	0.02829	0	11
Ivobase CAD	11	0.0823	0.04677	0.0141	0.00219	0	11
FormLabs	11	0.06546	0.01886	0.00569	3.55829E-4	0	11

Storage

	N	Mean	SD	SEM	Variance	Missing	NonMissing
0	15	0.15764	0.14597	0.03769	0.02131	0	15
10	18	0.06296	0.01934	0.00456	3.74037E-4	0	18

Overall

	N	Mean	SD	SEM	Variance	Missing	NonMissing
	33	0.106	0.10869	0.01892	0.01181	0	33

Interaction

		N	Mean	SD	SEM	Variance	Missing	NonMissing
ProBase Hot	0	5	0.28244	0.20387	0.09117	0.04156	0	5
	10	6	0.07673	0.01601	0.00654	2.56297E-4	0	6
Ivobase CAD	0	5	0.11366	0.05444	0.02435	0.00296	0	5
	10	6	0.05616	0.01414	0.00577	2.00027E-4	0	6
FormLabs	0	5	0.07681	0.00123	5.49484E-4	1.50966E-6	0	5
	10	6	0.05599	0.02177	0.00889	4.7399E-4	0	6

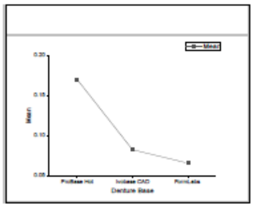
ANOVA

Overall ANOVA

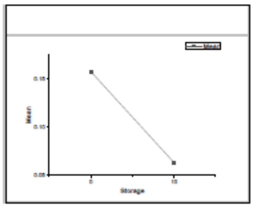
	DF	Sum of Squares	Mean Square	F Value	P Value
Denture Base	2	0.08042	0.04021	5.94067	0.00728
Storage	1	0.07333	0.07333	10.83391	0.00278
Interaction	2	0.05226	0.02613	3.86065	0.03352
Model	5	0.19525	0.03905	5.769	9.537E-4
Error	27	0.18276	0.00677	--	--
Corrected Total	32	0.378	--	--	--

Figure 17. Descriptive statistics for Coe Comfort

Factor A



Factor B



Interaction

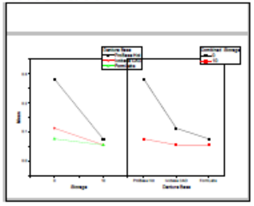


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Figure 18. Graphic representation of 2-way ANOVA

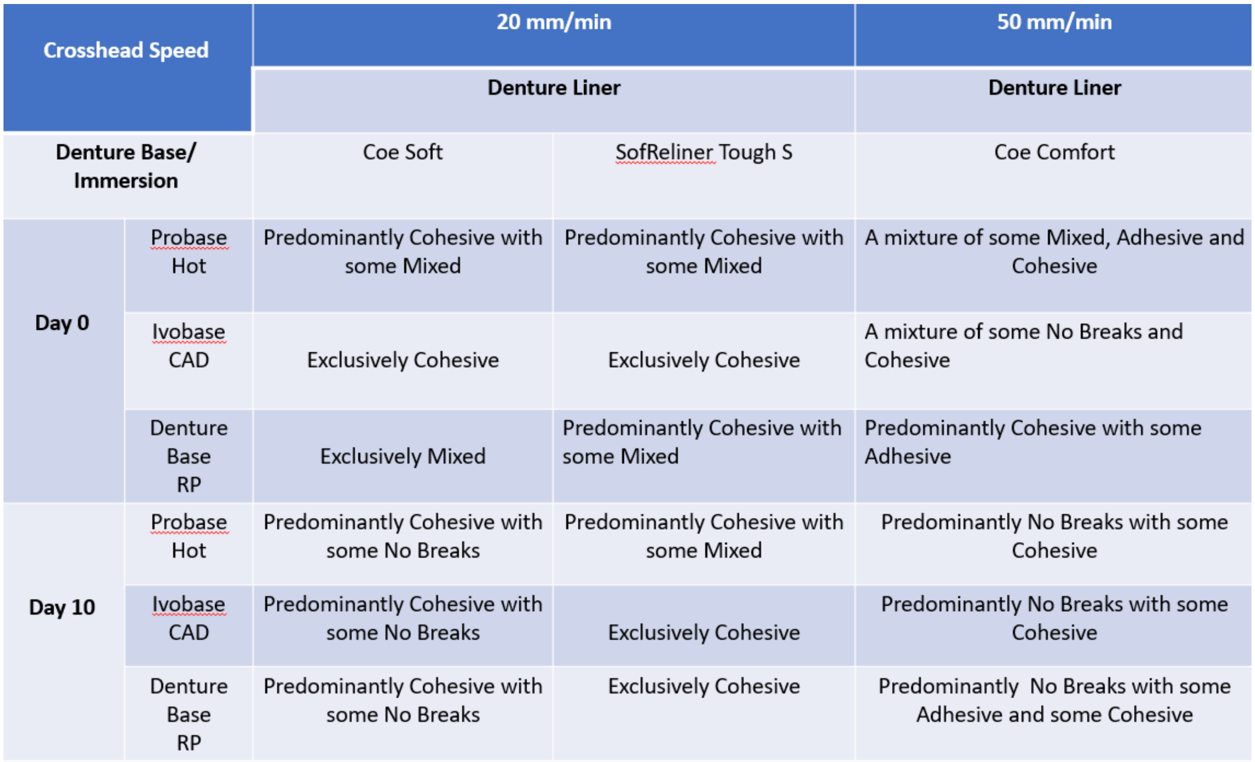
3.3 Failure Modes

As for the observed modes of failures in this study, some variation was seen based on the liner material that was used and if the samples were immersed or not. Failure modes encountered in this study are shown in Table 6.

SofReliner Tough S predominantly showed cohesive failure with some mixed failures with all the denture bases at both 0 and 10-days and regardless of water immersion.

On the other hand, Coe Soft predominantly showed cohesive failure with some mixed failures with all denture bases and no immersion. Its interesting to note that water immersion for 10-days seems to influence the failure mode. Failure mode of Coe Soft was still predominantly cohesive for all the denture bases but after 10-day water immersion some liner samples showed no break along with no debonding.

Coe Comfort results showed a similar pattern to Coe Soft. At 0-days, the failure modes had some mixed, some adhesive and some cohesive failure modes but after water immersion failure mode was predominantly no break or debonding with some cohesive and some adhesive failures.



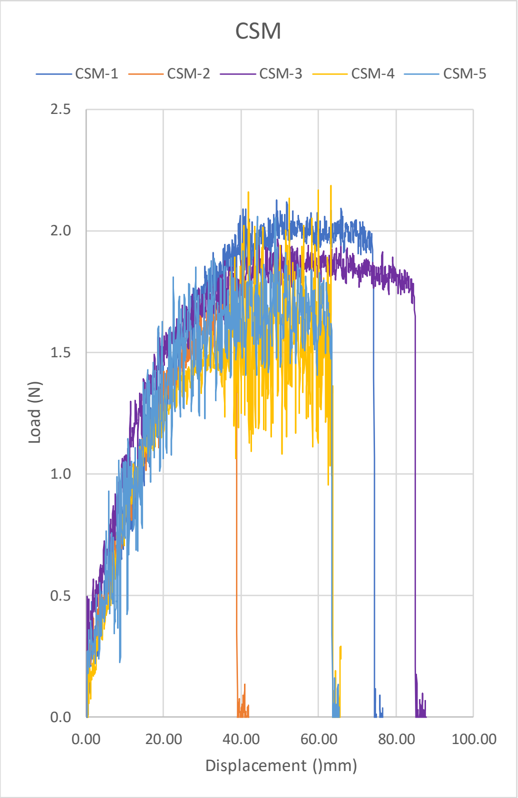
Crosshead Speed		**20 mm/min**		**50 mm/min**
		Denture Liner		**Denture Liner**
Denture Base/ Immersion		Coe Soft	SofReliner Tough S	Coe Comfort
Day 0	Probase Hot	Predominantly Cohesive with some Mixed	Predominantly Cohesive with some Mixed	A mixture of some Mixed, Adhesive and Cohesive
	Ivobase CAD	Exclusively Cohesive	Exclusively Cohesive	A mixture of some No Breaks and Cohesive
	Denture Base RP	Exclusively Mixed	Predominantly Cohesive with some Mixed	Predominantly Cohesive with some Adhesive
Day 10	Probase Hot	Predominantly Cohesive with some No Breaks	Predominantly Cohesive with some Mixed	Predominantly No Breaks with some Cohesive
	Ivobase CAD	Predominantly Cohesive with some No Breaks	Exclusively Cohesive	Predominantly No Breaks with some Cohesive
	Denture Base RP	Predominantly Cohesive with some No Breaks	Exclusively Cohesive	Predominantly No Breaks with some Adhesive and some Cohesive

Table 6. Failure modes of each resilient denture liner bonded to each denture base resin material with and without water immersion. No Break denotes liner stretched without fracture or debonding

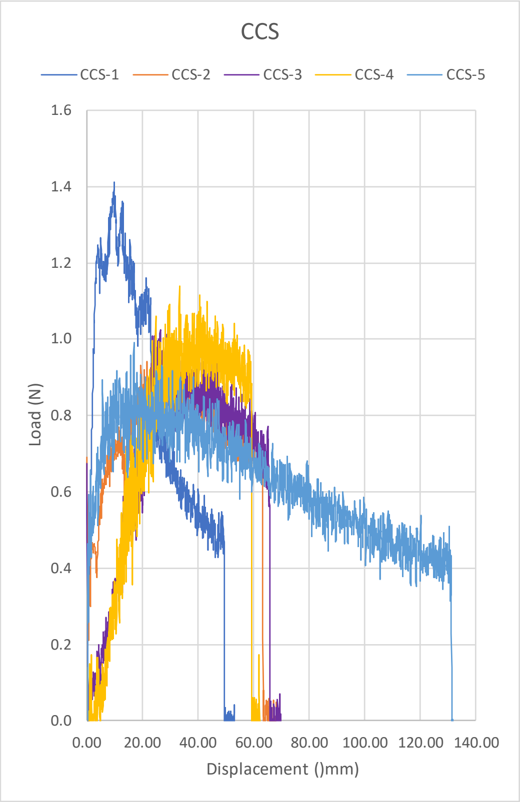
3.4 Raw Data

a. Day-0 data

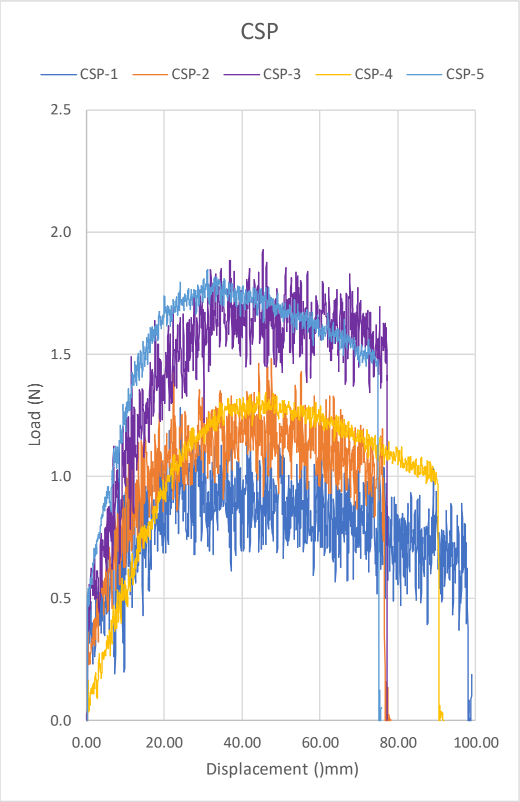
All the raw data generated during day-0 testing is shown in Figure 19. Stress- strain graphs were generated to represent test data in respective test groups. Various test groups represented in these graphs are described as follows


CSM
CSM-1
CSM-2
CSM-3
CSM-4
CSM-5
Load (N)
2.5
2.0
1.5
1.0
0.5
0.0
0.00
20.00
40.00
60.00
80.00
100.00
Displacement ()mm)

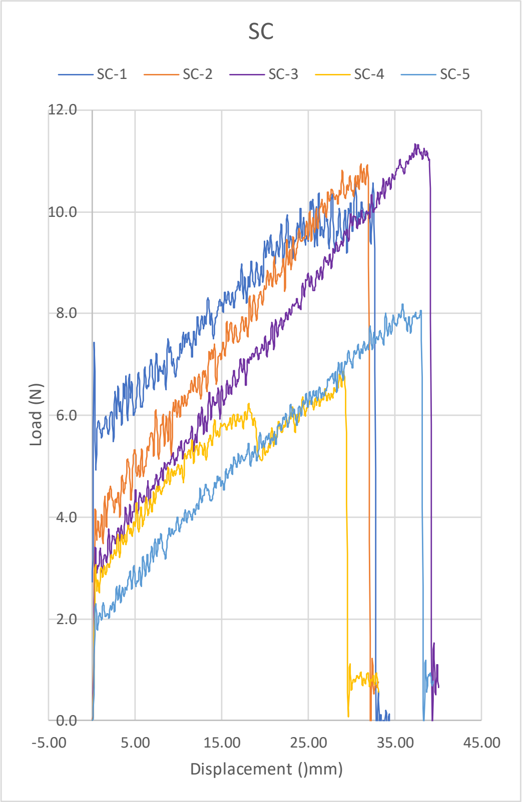
a


CCS
CCS-1
CCS-2
CCS-3
CCS-4
CCS-5
Load (N)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
Displacement ()mm)

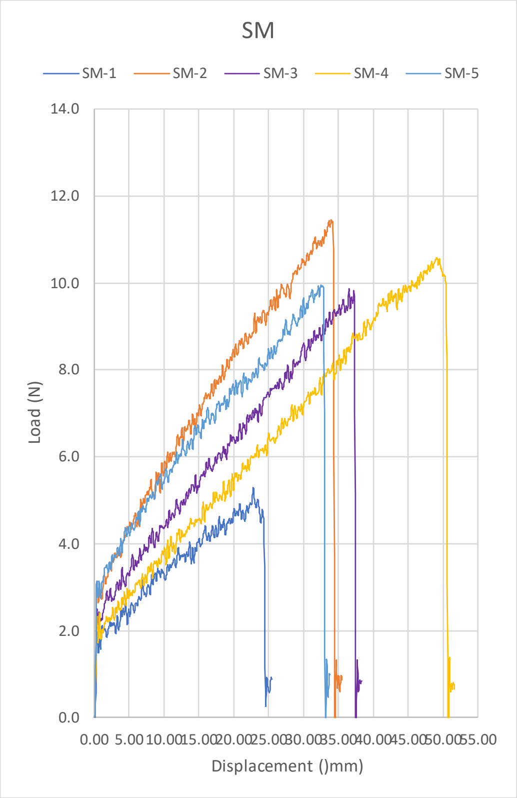
b


CSP
CSP-1
CSP-2
CSP-3
CSP-4
CSP-5
Load (N)
2.5
2.0
1.5
1.0
0.5
0.0
0.00
20.00
40.00
60.00
80.00
100.00
Displacement ()mm)

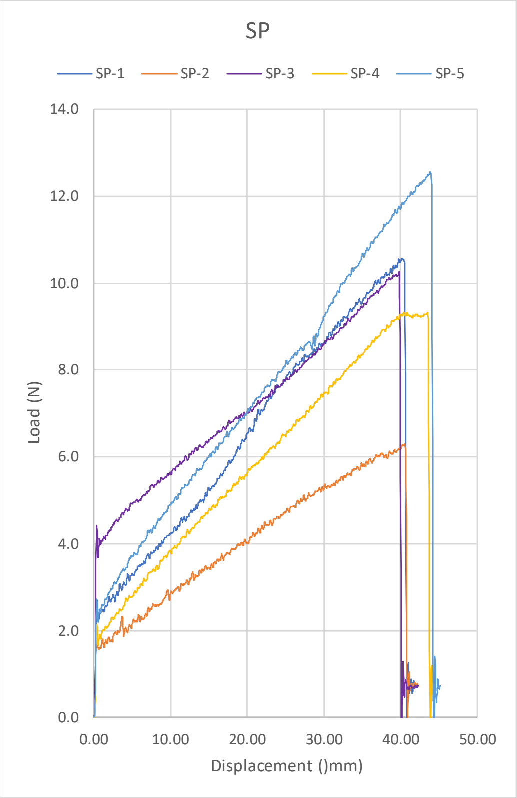
c


SC
SC-1
SC-2
SC-3
SC-4
SC-5
Load (N)
12.0
10.0
8.0
6.0
4.0
2.0
0.0
-5.00
5.00
15.00
25.00
35.00
45.00
Displacement ()mm)

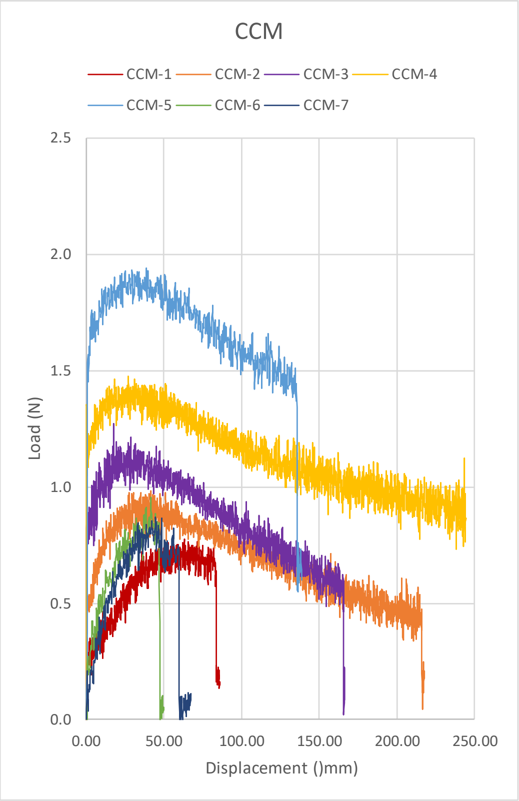
d


SM
SM-1
SM-2
SM-3
SM-4
SM-5
Load (N)
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
50.00
55.00
Displacement ()mm)

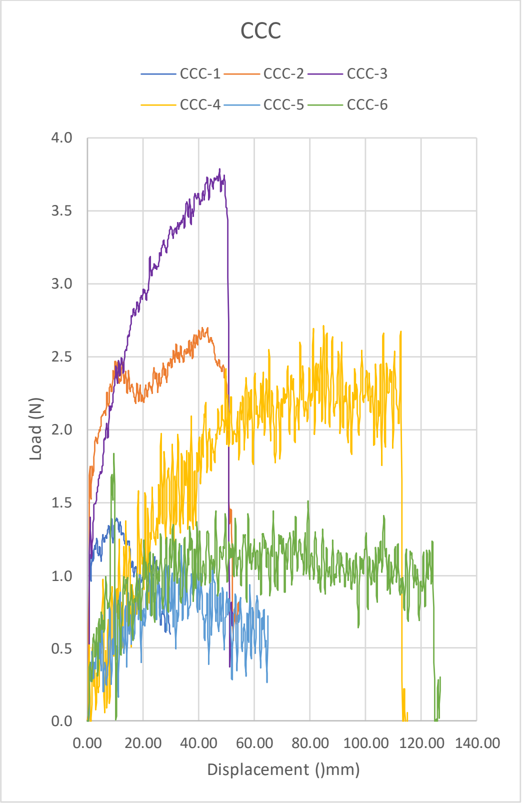
e


SP
SP-1
SP-2
SP-3
SP-4
SP-5
Load (N)
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0.00
10.00
20.00
30.00
40.00
50.00
Displacement ()mm)

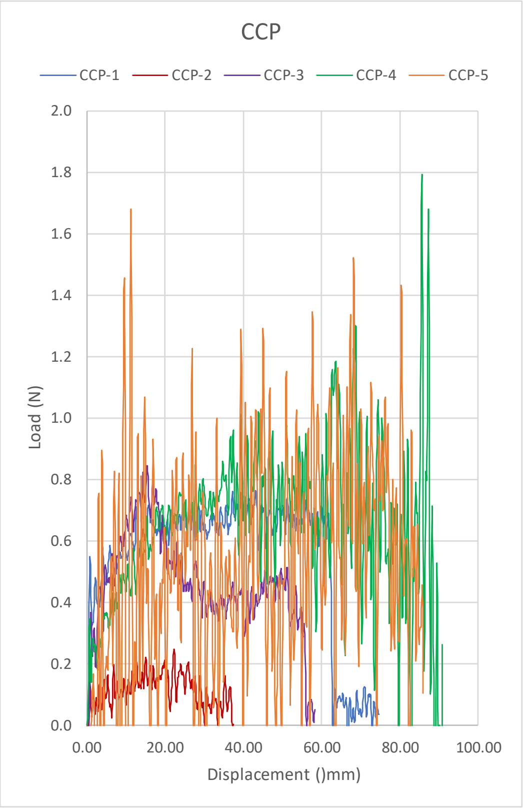
f


CCM
CCM-1
CCM-2
CCM-3
CCM-4
CCM-5
CCM-6
CCM-7
Load (N)
2.5
2.0
1.5
1.0
0.5
0.0
0.00
50.00
100.00
150.00
200.00
250.00
Displacement ()mm)

g


CCC
CCC-1
CCC-2
CCC-3
CCC-4
CCC-5
CCC-6
Load (N)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
Displacement ()mm)

h



i

Figures 19. Graphic representation of day-0 raw data

a. CSM – Coe Soft on Milled base, b. CCS – Coe Soft on Conventional base, c. CSP - Coe Soft on Printed base, d. SC – Silicone on Conventional base, e. SM- Silicone on Milled base, f. SP - Silicone on Printed base, g. CCM- Coe Comfort on Milled base, h. CCC – Coe Comfort on Conventional base, i. CCP – Coe Comfort on Printed base.

Denture bases in these graphs are described as Milled base – IvoBase CAD, printed base – Denture Base RP, Conventional base – ProBase Hot

Tokuyama Sofreliner Tough S samples showed least amount of extension but were able to sustain highest loads before fracture occurred.

Coe Soft samples showed much more extension than silicone samples before fracture occurred, and yield point is achieved overall at much lower load than silicone samples.

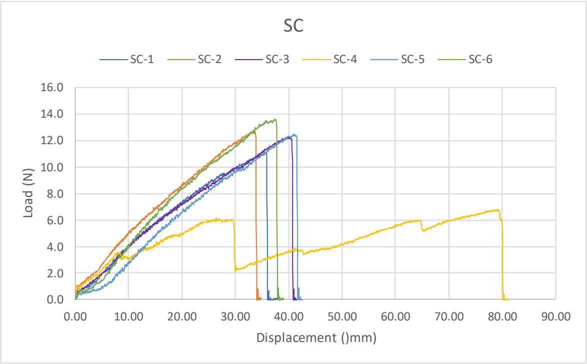
Coe Comfort samples showed comparatively more extension as compared to Coe Soft samples and yield point was achieved at comparatively lower load than Coe Soft samples. This denotes Coe Comfort are the most elastic materials and have the lowest tear strength.

a. Day-10 data

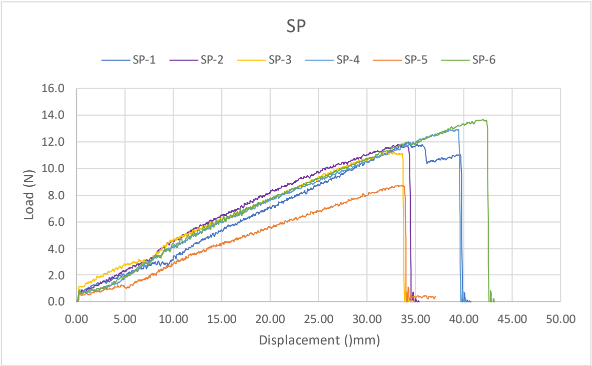
All the raw data generated during day-10 testing is shown in Figure 9. Stress- strain graphs were generated to represent test data in respective test groups. Various test groups represented in these graphs are described as follows:

a. SC – Silicone on Conventional base, b. SP - Silicone on Printed base, c. SM- Silicone on Milled base, d. CSC – Coe Soft on Conventional base, e. CSM – Coe Soft on Milled base, f. CSP - Coe Soft on Printed base, g. CCP – Coe Comfort on Printed base, h. CCM- Coe Comfort on Milled base, i. CCC – Coe Comfort on Conventional base

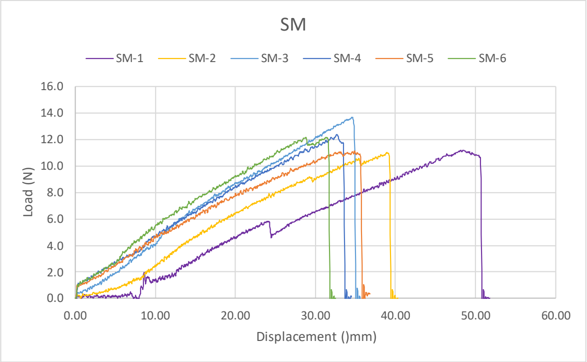
Denture bases in these graphs are described as Milled base – IvoBase CAD, printed base – Denture Base RP, Conventional base – ProBase Hot



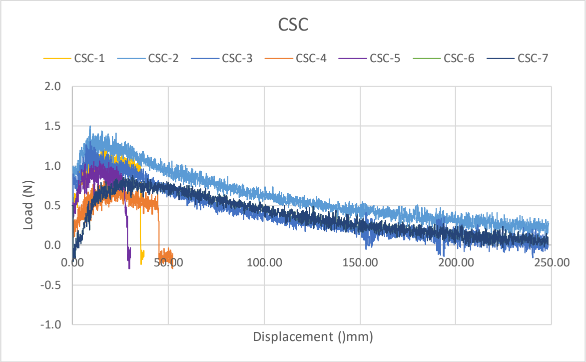
a



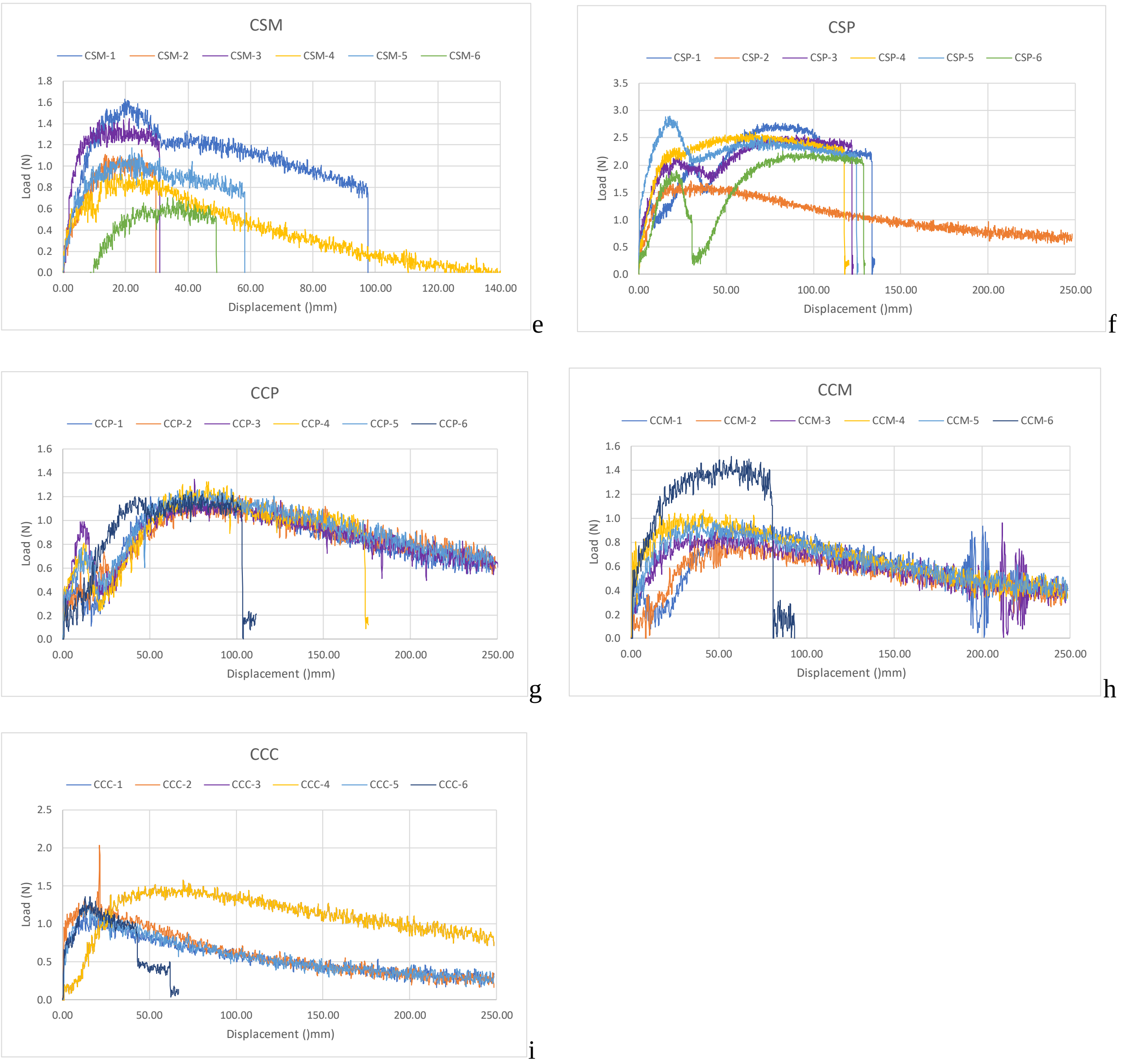
b



c



d



Figures 20. Graphic representation of day-10 raw data

Tokuyama Sofreliner Tough S samples behaved similarly on day-10 as compared to day-0.

Coe Soft samples showed much more extension at day10 as compared to day 0. Its important to note that comparatively more samples kept on stretching without showing fracture at day 10.

Coe Comfort samples showed similar increase in elasticity as Coe Soft because of 10-day water immersion.

Chapter 4

Discussion

Loss of adhesion between the denture base and the reline material is the most common and most important denture liner failure (Kreve et al, 2019). It is also the most common reason for failure of soft relined dentures (Wright et al, 1984). Delamination rates were found to be around 20% for indirect silicone based reline materials in a 6-year retrospective study (Schmidt et al, 1983).

For the main study, in first part of this thesis, we evaluated peel bond strength of IvoBase CAD and Denture Base RP samples when relined with Tokuyama Sofreliner tough S and Coe Soft, in comparison to ProBase Hot. For second part of this research, we evaluated peel bond strength of IvoBase CAD and Denture Base RP samples when relined with Coe Comfort, in comparison to ProBase Hot. Effects of 10-day water immersion on peel bond strength of tested materials was also evaluated.

Results of this study show that mean peel bond strength values are significantly higher for Sofreliner Tough S (Mean1.64 ± 0.17 MPa) as compared to Coe-soft (Mean 0.20 ± 0.107 MPa) liner irrespective of denture base or 10-day water storage. Hence first null hypothesis was rejected.

This result is consistent with another recent study comparing peel bond strength of silicone denture liner with plasticized acrylic denture liner. It was found that the silicone-based liner employed in that study, had significantly higher average maximum bond strengths achieved during the peel test (Young et al, 2021).

Our result, though differ from Kutay et al (1994) who tested tensile and 180° peel bond strength between Molloplast B and Coe Super Soft bonded to Lucitone 199 acrylic resin denture base samples. Both tensile and peel bond strengths of silicone-based long-term denture liner were found to be much lower as compared to plasticized acrylic-based long-term denture liner (Kutay et al, 1994).

Results of our study also showed that type of denture bases did not lead to significant difference in peel bond strengths of both Coe Soft and Sofreliner Tough S (P = 0.5274). However, surprising results were seen when we evaluated interactions of denture bases with both the resilient liners. We found significant interaction between different tested denture bases and both Sofreliner Tough

S and Coe Soft. These interactions between denture base test sample and overlying liner, led to significant differences in peel bond strength ($p < 0.05$). Similarly, type of denture base also led to statistically significant differences in peel bond strengths of Coe Comfort ($P = 0.00728$). Thus, second null hypothesis was only partially rejected.

Our results are consistent with Takahashi et al (2001). They also concluded that type of denture base polymer and denture reline polymers affected the bond strength between them (Takahashi et al, 2001).

Adhesive failure between denture base and resilient lining materials is characterised by chemical interactions between denture base, liners and the adhesives being employed (Emmer et al, 1995). It is known that bond strength between the existing denture base resin and added reline resin is affected by the chemical composition of these two resins (Kim et al, 2014). A mutual solubility or compatibility of the denture base polymer and the overlying liner polymer is essential to establishment interwoven IPN connection required for a durable bond (Takahashi et al, 2000). PMMA based denture reline materials have been shown to bond stronger with PMMA denture bases due to similar chemistry (Arena et al, 1993). Silicone-based long-term denture liners are chemically different than PMMA denture bases and this affects their bond strengths (Pesun et al, 2019). To overcome this problem use of proper silicone adhesives is recommended for a strong durable bond (Murata et al, 2008). This adhesive normally consists of an organic solvent and a monomer, which will dissolve PMMA and react with both silicone and resin materials, leading to interpenetrating network formation (Demir et al, 2011, Muddugangadhar et al, 2020).

Difference in chemical composition of silicone-based long-term denture liners than most PMMA based dentures has resulted in bond strengths of silicone-based long-term denture liners being considered inferior to plasticized acrylic-based long-term denture liners. (Chladek et al, 2014, Özdemir et al, 2018).

A compatible manufacturer recommended adhesive was used, in our present study, with Sofreliner Tough S to ensure a good bond with the test denture specimens. It can be postulated that the adhesive provided with Sofreliner Tough S may have contributed to its higher peel bond strength in our testing. This inference agrees with another study evaluating adhesive strength and compliance of soft lining materials (McCabe et al, 2002). Authors concluded that mode of adhesive failures in their study were affected by the choice adhesive employed in the study (McCabe et al, 2002).

Originally Craig and Gibbons in 1961 had concluded that adhesion values of 10 pounds per inch for resilient liners were clinically sufficient. Further to this in 1992, 4.5kg/cm² or 0.44MPa were established as clinically acceptable minimum bond strength between resilient denture lining materials and the denture base (Kawano et al, 1992).

Based on our results it can be inferred that Tokuyama Sofreliner Tough S (Mean1.64 ± 0.17 MPa) has peel bond strength much higher than accepted clinical norm of minimum peel bond strength of 0.44 MPa, while Coe Soft (Mean 0.20 ± 0.107 MPa) does not.

This however may not be a correct inference due to the testing method employed in this study. It has been concluded in a systematic review that testing method has a very important effect on the denture reline bond strength measurements (Özdemir et al, 2018).

Multiple tests like peel, tensile, shear, fatigue, creep, impact, and cleavage have been devised over years to evaluate adhesive bond strength of reline materials (Al-Athel et al, 1996). Bond strength of resilient denture liners is dependent upon nature and direction of debonding force, liner thickness, nature of adhesive agent, liner processing method and nature of denture base (Demir et al, 2011).

Test method effects bond strength measurements due to difference in mechanisms of force application to the bonding interface between denture liner and the denture base (Özdemir et al, 2018). A point in case being that it is generally accepted that peel bond strength is approximately 1/10th of the measured tensile strength of similar relined samples (Maeda et al, 2012).

Test of bond strength between hard liners and denture base is more commonly tested by 3-point bending tests (Takahashi et al, 2001).

Resilient liners have been tested for bond strength with both tensile and shear bond strength testing with shear testing thought to be more clinically representative (Takahashi et al, 2001). Peel bond strength tests and shear bond strength tests though, are considered difficult to interpret (Chladek et al, 2014). That explains why tensile tests for resilient liners are popular and was concluded to be the most commonly preferred test in a systematic review of 57 included studies (Özdemir et al, 2018). But it needs to be emphasized as a caution that tensile bond strength of resilient liners is least clinically relevant (Kawano et al, 1992).

It has been suggested that bond strength testing for soft denture liners may be best accomplished by a peel bond test (Braden et al, 1995).

Kendall in 1975, first describe peel test to calculate force required to peel an elastic film from a rigid substrate. Advantage of peel test was that it can measure both elastic deformation of the lining material and peel energy required for debonding (Kendall et al, 1971). Then in 1981, Wright utilized peel test with a peeling angle of 180° to evaluate adhesion properties and measure force needed to peel soft lining materials off the rigid PMMA denture bases (Wright et al, 1981). Since then, peel bond testing has been utilized by various authors over several years like Sinobad et al, (1992), Kutay et al, (1994), Young et al, (2021) and many others.

It has been observed that delamination of any resilient liners usually starts at the exposed edges of the lining. Resilient liner debonding can thus be considered akin to a peeling process (McCabe et al, 2002). Since peel test leads to stress concentration at the edges of the liner joint it is considered more clinically representative of the failure mode of soft reline materials in use (Demir et al, 2011). It has been postulated that 180° peel test closely stimulates masticatory force that is clinically applied at interface between resilient denture liner and the denture base. Thus, 180° peel test is supposed to be the best measure of interstitial bonding strength (Maeda et al, 2012).

But the problem with peel test is two-fold. First is its difficult to interpret and secondly due to horizontal component of applied testing force peel bond testing generates high risk of cohesive failure (Chladek et al, 2014). Most of the studies utilizing peel bond method of testing adhesive strength noticed predominantly cohesive failure of denture liner samples (Chladek et al, 2014, Maeda et al, 2012, Demier et al, 2011, Alcantara et al, 2012).

Study by Kawano et al (1992), that established clinically acceptable minimum peel bond strength standards for resilient liner; also showed predominantly cohesive failures. Other authors also concurred that peel bond tests are bedevilled with soft liner breakage rather than intended peeling process (Braden et al, 1995). Infact due to this exact reason of predominantly cohesive failures during testing, peel bond test was deemed least satisfactory in a study comparing effect of various test methods on bond strength values (Al-Athel et al, 1996). Tendency of soft reliners to fracture during a peel bond test was previously addressed by Emmer et al in 1995 in their study on bond strengths of permanent soft denture liners bonded to the denture base. These authors suggested use of term “strength failure” for such cohesive failures rather than the term “bond failure” (Emmer et al, 1995).

It has been said that predominantly cohesive failures within the liner material do not allow a satisfactory and reliable measurement of peel bond strength (Alcantara et al, 2012). These authors postulate that cohesive failure mode provides information regarding the lining material itself rather than the peel bond strength (Alcantara et al, 2012). Thus, it can be safely assumed that cohesive failure during peel bond testing indicate a poor tear resistance.

Based on the observations of all these authors, another way to infer our results could be that Tokuyama Sofreliner Tough S in this study is a stronger material with much higher tear strength than Coe Soft.

Now this inference of our result is inconsistent with Wright et al (1980) who concluded in a study that generally speaking tissue conditioner type materials and silicone rubber reliners were weaker than plasticized acrylic denture liner polymers.

But our result of silicone- based resilient denture liner being stronger makes sense if one considers the nature of plasticizer acrylic denture reline material we used in this study. Coe Soft is an autopolymerizing plasticized acrylic denture reline polymer and may be used for longer term over a few months. It has been marketed as such on its manufacturer’s website. Though for practical purposes it should be considered an “elasto-viscous gel” due to its amorphous non-crosslinked structure more akin to a traditional tissue conditioner (Braden et al, 1995). Once we realize the true nature of Coe-Soft liner material it is no surprise that it was found to be weaker than Sofreliner tough S in this study.

Thus, inference of our results that Sofreliner Tough S is stronger than Coe Soft agrees with another study evaluating durability of peel bond of resilient denture liners to various acrylic denture base resins (Maeda et al, 2012). All the included Coe Soft samples exhibited cohesive failure which authors attributed to their lower breaking strength due to their inherent non-crosslinked amorphous polymer nature (Maeda et al, 2012).

As for the observed modes of failures in our current study, a predominantly cohesive failure or mixed failure was noticed. Adhesive failures were scarcely noted and were limited to Coe Comfort.

In this current study, bond failures were visually observed and then classified into three different categories: adhesive, cohesive and mixed. This methodology was based on Alcantara et al study in 2012 (figure 12).

Maeda et al (2012) had described another way to characterize soft liner failures duirng peel bond testing as tear, peel or snap, which was based on where the failure occurred in relation to the bonded area (figure 12). While using a very similar classification for observed liner failure Alacantara et al (2012) further expounded on it. These authors sugegsted that if the liner stretched and broke in the nonbonded area, it was termed a snap failure while if liner breakage was noticed in the bonded zone, it was referred as a tear. Mixed failure were considered when areas of both cohesive and adhesive failure were seen (Alacantara et al 2012).

Since tear kind of soft liner fracture may be easily considered in both cohesive and mixed failure by some observors, to avoid this confusion we decided to go with a simple classification of debonding modes for our study: adhesive, cohesive and mixed.

In our present study, bonding failure was deemed to be adhesive in nature when peeling occurred between resilient denture liner and the denture base. It was deemed to be cohesive when there was tearing of reline material regardless of where this tearing occurred. Some of these cohesive failures were noticed to be in the bonded zone denoting that material had started to debond from the denture base before it stretched and tore. Mixed failures were deemed to have occurred when both adhesive and cohesive liner failures could be seen on the surface of the denture base (Figure 13).

Our observation of majority of failures being fracture of resilient liner materials is in general agreement with most of the previously conducted studies on peel bond strength. Most of the studies utilizing this method of testing peel bond strength noticed predominantly cohesive failure of denture liner samples (Chladek et al, 2014, Maeda et al, 2012, Demier et al, 2011, Kawano et al, 1992, Braden et al, 1995, Emmer et al, 1995, Kutay et al, 1994, Alcantara et al, 2012) also faced predominantly cohesive failures within the liner material. Demir et al (2011) tested bond strength of 2 silicone based resilient denture liners and found cohesive failures in all their tested samples as well. As previously discussed, peel bond tests are bedevilled with soft liner breakage rather than peeling (Braden et al, 1995) and thus was deemed least satisfactory in a study comparing effect of various test methods on bond strength values (Al-Athel et al, 1996). All this has eventually led to the suggestion for use of term “strength failure” for such cohesive failures in resilient liner materials rather than the term “bond failure” (Emmer et al, 1995). Thus, we can assume that cohesive failure mode provides information regarding the lining material itself, indicating poor tear resistance (Alcantara et al, 20120).

Considering this discussion, an interesting quandary may come to mind of any reader now regarding interpretation of our results.

As by far most failures in this study are predominantly cohesive in nature with some mixed failures, and we know peel bond test is basically giving information regarding strength of the material if cohesive failures are occurring. Then a prudent question may be how we reconcile these two facts and decide that the measurements we are getting in this study are for peel bond strength of the materials tested.

This same question has previously been faced and answered by other authors who have tested peel bond strengths of resilient liners. First insight on this matter I believe was provided by Craig et al in 1961. They said that materials with lower tear strength will tear rather than strip away easily even if adhesive bond strength is low. If tear strength of reline material is higher than one may find more adhesive failures (Craig et al, 1961). When faced with predominantly cohesive failures during peel bond testing, another group of authors postulated that since most of their samples were starting to peel before they showed cohesive failure, it may be concluded that tear strength of tested liner materials was equal to or approaching the peel bond strength of the tested samples (Maeda et al, 2012).

Similar observations were made in another study when facing mostly cohesive failure mode during peel bond testing (Alcantara et al, 20120). However, as there were some mixed and adhesive failures at similar force application in their samples as well, which as per these authors suggested that cohesive values were approaching close to bond strength values in most cases (Alcantara et al 2012). Al- Athel et al (1996) also concluded that peel bond strength of all the tested silicone denture lining materials was stronger than the strength of lining materials themselves due to cohesive failures noticed in tested silicone liners.

McCabe et al (2002) also brought to our attention the fact that the stresses on bond interface depend inter alia upon the compliance of a soft material. Hence a lower compliance material will have higher stress concentration and thus should debond quicker as compared to a high compliance material. In case of a softer material, an effective bond can thus be demonstrated by a cohesive mode of failure within the material during testing (McCabe et al, 2002).

Lack of adhesive bonding strength or durability can be a result of lower tear strength of the denture lining material as well (Kreve et al, 2019), which we believe is the case in our study with Coe Soft and Coe Comfort.

After consideration of all these factors, it can now safely be said that based on our results both Coe Soft (0.22546 ± 0.09066 MPa) and Coe Comfort (Mean 0.15764 ± SD 0.14597 MPa) as tested in our study without water insertion, may have peel bond strength approaching close to clinically acceptable minimum peel bond strength.

It is important to note that, if cohesive failures of liner samples during peel bond strength testing leads to only conclusion that bond strength of the tested material exceeds the cohesive strength of the material, as we did in the present study. Then it may be advisable to conduct additional fatigue tests like aging or subject samples to additional compressive or shear forces as well (Chladek et al, 2014).

For in-vitro testing, Chen et al (2021) had suggested use of aging methods. Water immersion aging which will cause hydrolysis of bonding interface, while thermocycling aging will cause thermal stresses. These aging methods will help mimic long term stresses during clinical service that may be applied to the bonding interface between denture base and lining materials (Chen et al, 2021). It has been calculated those 10000 cycles during thermocycling test will equate approximately 3 years of clinical use of a relined denture (Maeda et al, 2012). Thermocycling may lead to an increase in peel bond strength of some direct chair-side resilient denture liners which can be attributed to effect of heat applications during testing leading to enhanced polymerization (Maeda et al, 2012). Strength of still other long-term lining materials may decrease with thermocycling, and this is dependent on chemical composition of liner material (Chladek et al, 2014).

Due to lack of a thermocycling machine in our school it was decided to test the materials in this study after a water immersion aging cycle.

Results of our current study show that there is a generalised trend for reduction of peel bond strength values with 10-day water immersion. Results show that 10-day water immersion led to statistically insignificant changes in peel bond strength values of both Coe Soft and Tokuyama

Sofreliner Tough S (P = 0.4118). However, interactions between these liners, type of denture bases and 10-day water immersion were statistically significant ($p < 0.05$). Coe Comfort showed statistically significant differences in peel bond strength after 10-day water immersion ($p < 0.05$). Thus, third null hypothesis was only partially accepted as well.

This finding concurs with Wright et al (1980); who studied rupture properties of denture soft lining materials. They found water immersion for 6-months deteriorated bond strength of all reline materials (Wright et al, 1980). Water sorption will also lead to decrease in tear strength of the resilient liner materials (Craig et al, 1961).

On other hand due to loss of plasticizers during water immersion, this artificial aging may be expected to introduce brittle behaviour to the soft lining material and changes failure mode to more adhesive failures (Emmer et al, 1995).

This was only observed to a limited extent in our study though. We only noticed adhesive failure after 10 days water immersion in a few of the Coe Comfort (tissue conditioner) lined Denture Base RP (3d printed denture base) samples. What was more obvious though in our study was that both Coe Comfort and Coe Soft samples showed an increase in no breakage or no delamination after 10 days of water immersion test. Instead of breaking or peeling off, the samples kept on stretching without break till the travel distance (105mm) of the testing machine was used up and machine couldn’t test the samples more. This phenomenon has been called “necking” in previous studies by McCabe et al (2002). Necking in engineering parlance has been described as “tensile deformation where relatively large amounts of strain is localized disproportionately in a small region of the material”. This is exactly what was noticed in current study with (Coe Comfort) tissue conditioner lined samples; thin threads of the material kept on stretching without fracture similar to necking.

Increased elasticity of the Coe Comfort that allowed necking is also extremely beneficial to its function as a tissue conditioner. As previously elaborated by Braden et al (1995); Coe Soft (plasticized acrylic) has a very similar chemical structure to Coe Comfort (tissue conditioner) thus its no surprise that some of Coe Soft samples also demonstrated similar necking behaviour

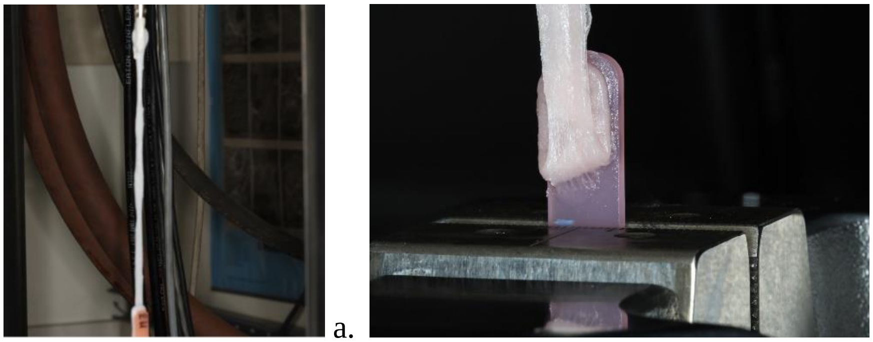

a. b.

Figure 21. a. Necking and Stretching obvious in Coe Comfort sample during testing, b. Peeling starting in a Coe Soft sample on a printed denture base before too much stretching of the liner occurred.

There is another very interesting aspect of viscoelastic properties of resilient liners that was previously discussed but should be again considered here. As a soft material subjected to peeling has stresses dependent upon the compliance of softer material (McCabe et al, 2002). It should be considered that a softer and more elastic material like Coe Soft or Coe Comfort in such cases will rather be expected to stretch and neck before breaking

Since Emmer et al (1995) considered loss of plasticizers during water immersion may be expected to introduce brittle behaviour to the soft lining material. But we noticed necking and stretching of both Coe Soft and Coe Comfort materials. This discrepancy may be explained by the short duration of water storage that we used in this study as compared to Emmer et al (1995). Water that is diffused into the denture liner polymers, acts as a plasticizer and also may decrease strength of the polymers (Takahashi et al, 2000). However, effects of water storage seem to plateau after 1-4 months, and a state of equilibrium is reached (Takahashi et al, 2000).

So, from our results it should be inferred that in short terms, Coe Soft and Coe Comfort may become more plasticized due to water sorption and thus enhance patient comfort.

This plasticizing effect on other hand was not seen with Tokuyama Sofreliner Tough S. Since water sorption of silicone-based denture liners is related to its filler constituents (Braden et al, 1983) and normally filler content of silicone-based liner materials is low even for direct RTV denture liners like Tokuyama Sofreliner Tough S (Braden et al, 1983).

Other important factor to consider in peel bond strength values achieved in this study may also include cross head speeds involved. Peel specification ASTMD903-93 described peeling rate of

152 mm/min but a slower rate is expected to promote more adhesive failures than cohesive failures, so they used crosshead speeds of 5mm/min. (Demir et al, 2011). Wright et al (1980) tried this method of lower cross head speeds and get more adhesive failures but failed to achieve adhesive failures in all the samples. However, it was noticed that more cohesive failures were found at 20mm/min than at 60mm/min at which cross head speed a tendency for more adhesive failures was noticed (Al-Athel et al, 1996). As in the pilot study with Coe Comfort (tissue conditioner) at a cross head speed of 20mm/min; we didn't achieve any kind of fractures or delamination in first few samples tested and instead all we got was stretching of all the samples in pilot study. A conscious decision was made to discard all the tissue conditioner pilot study data and instead a decision was made to recreate this part of study with Coe Comfort lined samples at an increased crosshead speed of 50mm/min.

Interestingly with a crosshead speed of 50 mm/min, at 0-days without water immersion, we only got a few no break/ no debond situations and that too only with Coe Comfort lined IvoBase CAD samples. Mostly we observed a mix of cohesive, adhesive, and mixed failures when Coe Comfort was tested with other ProBase Hot and Denture Base RP samples. But we did not consider the plasticizing effect of water absorption and thus ended up with predominantly no break/ no debond failures with some cohesive and adhesive failures as a result of 10-day water immersion test even with increased crosshead speed of 50 mm/min.

Another factor that may be considered in relation to bond failures is thickness of the liner material employed in this study. A question may be correctly asked if increasing thickness of liner material to more than 3mm, would have induced more adhesive failures than were noticed in this study.

Measured bond strength and mode of failure are both shown to be affected by resilient liner thickness (Al-Athel et al,1996). It is important to note however that this study made this conclusion in relation to both shear and tensile strength of the tested liner materials. Also interesting is the fact that it was thinnest sections of Molloplast B samples which showed highest bond strengths (Al-Athel et al,1996).

As we were testing peel bond strength of resilient liner materials, it will be important to remember that liner material needs a certain level of compliance, so that it can be formed into a sample that can be readily subjected to 180° peel testing. Peel bond strength of a material is considered a function of compliance of the material with more adhesive failure expected in complaint materials

(McCabe et al, 2002). Compliance of resilient liners is not expected to change after a thickness of approximately 2mm (Craig et al, 1961, McCabe et al, 1996, Pesun et al, 2001). Optimal thickness of resilient denture liner material for clinical effectiveness is additionally, also recommended to be approximately 2mm (Schmidt et al, 1983, Murata et al, 2008).

Thus, it is expected that increasing thickness of Coe Soft and Coe Comfort will not necessarily prevent necking while increased thickness of Sofreliner Tough S may make it more resilient instead thus possibly leading to more cohesive failures. As such, we decided to limit liner thickness of samples to 3mm for testing. We believed that increasing thickness of resilient liners past 3mm will not only affect their viscoelastic properties and possibly corrupt results of this study but also makes this study less clinically applicable.

Direct gripping of the resilient denture liner in peel test may damage the integrity of the sample at gripped region and thus affect the tearing and subsequently peel bond strength measurements (Maeda et al, 2012). So, another important factor to consider when devising a peel test could be the gripping or grasping mechanism for your resilient liner materials. In some studies, a hole has been created in the reline material and the unbonded denture base, which would be further connected to a wire to apply the peeling force. Alcantara et al (2012), folded a portion of resilient liner material upwards from the non bonded denture base before attaching to a hook, to this end. We considered this mechanism, but we were concerned about tearing of Coe Soft and Coe Comfort due to their viscoelastic behaviour. As a result, we narrowed down to using alligator clips so as to not apply too much tearing force on to the samples, even then first few samples of Coe Comfort tore due to sharp teeth on alligator clamps. After some trial and error, ultimately, we decided to use electric alligator clamps with electric tape on teeth to grip the Coe Soft and Coe Comfort samples. With Sofreliner Tough S, we ran into opposite spectrum of the same problem. Due to resilient but less complaint nature of silicone-based denture liners, our taped electric alligator clasp assembly was unable to hold it. So, we tried by taking off the tape but still alligator clamps were unable to hold the Tokuyama Sofreliner Tough S. So, for the silicone-based long-term denture liner samples we used a regular light duty clamp with silicone inserts.

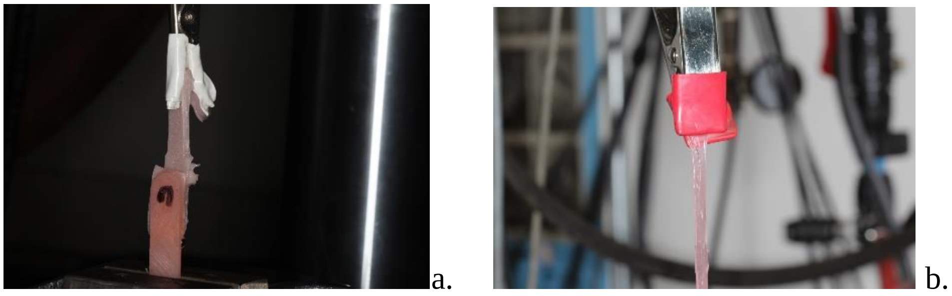

a. b.

Figure 22. Two different clasping assemblies use in this study a. Taped electric alligator clamps for Coe Soft and Coe Comfort, b. Light weight clamps with silicone insert for Sofreliner Tough samples.

Another problem that we faced during execution of this study was at conventional acrylic denture base sample fabrication using pack and cure technique. Firstly, as we were using stainless steel moulds, it is extremely difficult to control the rate of heat penetration into the acrylic. This method of polymerization lends itself susceptible to rapid boiling of monomer which may affect the surface characteristics and in turn may tarnish our results with the conventional denture base samples. Secondly due to sharp edges of the standardized stainless steel mould denture base, samples polymerized with sharp notches and grooves as a result of shrinkage during polymerization. These notches and grooves acted as areas of stress concentration and weak points where a lot of conventional denture samples broke during separation from mould, surface cleaning and polishing phase. Thirdly, due to polymerization shrinkage almost all these ProBase Hot samples were of different thicknesses.

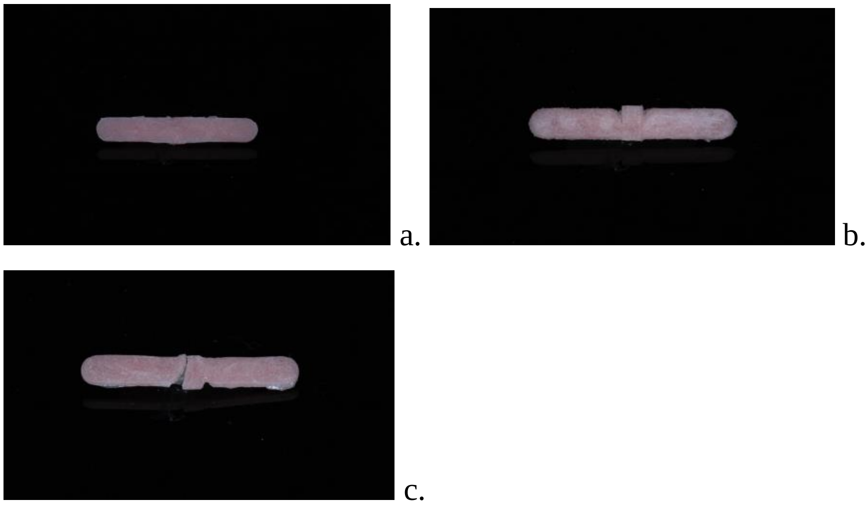

a. b.
c.

Figure 23. a. ProBase Hot sample, b. ProBase Hot sample with notching c. Broken ProBase Hot sample during separation from mould.

Thickness of denture base did not affect results of our study as equation we used only looked at the width and length of the reline material. So, difference in thickness of conventional heat processed denture base samples did not affect the results of our study.

Maeda et al (2012) described the eqaution we used to calculate the peel bond strengths of tested materials in this study.

$$Ps = F \times W^{-1} \left[\frac{1 + (1 + E)}{2} \right]$$

Here F is applied force at which failure occurred, W is the width of specimen in peeling area, E is the extension ratio of material (ratio of stretched to unstretched lengths of the liner material).

Equation used for calculation of peel bond strengths in this study takes into consideration both adhesive bond and elastic deformation of the resilient denture liner (Alcantara et al, 2012). Thus, this kind of peel bond testing by virtue of the equation used is able to provide stress-strain curves for the resilient liner materials being tested. Ability of peel bond strength tests to generate stress-strain graphs, has also been identified in another study reviewing soft lining materials (Braden et al, 1995). Soft liners are nonlinear in tension and area under stress-strain curve denotes energy required to break the lining materials (Braden et al, 1995). It would be interesting to generate stress-strain graphs from our calculations of peel bond strength using above mentioned equation. These can then be compared with stress-strain graphs generated through raw data to see if two data sets could be reconciled for confirming accuracy of calculations.

A sample stress-strain graph is provided here for reader's consideration (Figure 24) which can be used to compare with graphs generated with raw data (Figures 19 and 20).

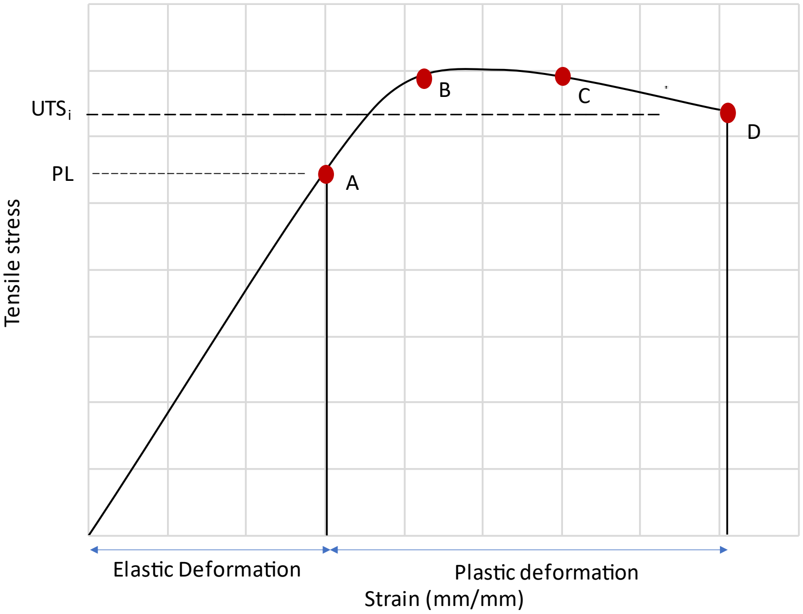


Figure 24. Sample stress- strain curve {Adapted from Sakaguchi et al, 2012}

Sample stress-strain curve illustrated in Figure 24 denotes amount of deformation of the sample at each point (A–D). Elastic deformation is the ability of the material to recover its original shape after load is released. Elastic modulus describes the relative stiffness or rigidity of a material, which is measured by the slope of the elastic region of the stress-strain graph. Elastic deformation is exhibited up to the proportional limit (PL). Yield Point is the point at which material starts to deform plastically. Plastic deformation is exhibited from PL to the failure point, where we register the stress at failure (SF). Plastic deformation is permanent strain or change in shape of object that results when stressed beyond elastic limit is applied (Anusavice et al 2012, Sakaguchi et al, 2012).

Stress- strain graphs generated with raw testing data (figure 19 and 20) show Coe Soft samples along with Coe Comfort samples have a lot of noise even at very low test loads. Sofreliner Tough S samples have very low noise at much higher test loads. This noise in raw data stress-strain graphs for Coe Soft and Coe Comfort, makes it much harder to read them and discern accurate data.

We tested all the samples using a 100-pound load cell. It can be assumed that if peel bond testing was to be performed with a lighter load cell, we may receive cleaner stress-strain curves with less noise and possibly more useful and readable data.

Attempts to describe physical properties accurately of all the tested materials based on these charts with a lot of noise will be futile effort due to ambiguity around data and beyond the scope of present study evaluating peel bond strengths.

There are some inferences though that may be drawn from the stress-strain graphs with raw data.

At 0-days, Sofreliner Tough S samples showed least amount of extension but were able to sustain highest loads before fracture happened, denoting these materials are resilient and not very elastic. But, Sofreliner Tough S seems to have higher tear strength.

Coe Soft samples showed much more extension than silicone samples before fracture occurred, and yield point is achieved overall at much lower load than silicone samples. This denotes that Coe Soft is a softer material than Tokuyama Sofreliner Tough S and have greater compliance as well.

Coe Comfort samples showed comparatively more extension as compared to Coe Soft samples and yield point as achieved at comparatively lower load than Coe Soft samples. This denotes Coe Comfort are the most elastic materials and have the lowest tear strength.

At 10-days Tokuyama Sofreliner Tough S samples behaved similarly as compared to day-0 thus very similar stress-strain graphs were produced. Coe Soft samples showed much more extension at day10 as compared to day-0. This denotes that Coe Soft got more elastic with water immersion possibly due to plasticizing effect of water diffusion during storage. Coe Comfort samples showed similar increase in elasticity as Coe Soft possibly also due to possible plasticizing effect of water diffusion during storage.

Limitations to this study

There are multiple and numerous study limitations that were encountered and identified during this experiment. Some of the more obvious problem is with using stainless steel moulds to fabricate conventional heat processed denture base samples as described previously. This limitation though can be easily remedied by creating standardized stone moulds in brass flasks which will mimic clinical reality of traditional denture processing. This at the same time will remedy problems of monomer boiling and notching of the samples.

For the first part of the study even though based on power calculation done by previous referenced studies, our sample size of 5 was adequate to get confidence level of 0.05. However, as Levene's test showed a 0.05 level, these population variances were significantly different. A higher number of sample sizes may be able to reduce some of these problems.

As discussed, when cohesive failure is expected, it is advisable to run either aging tests like thermocycling or water immersion tests. Due to lack of thermocycling equipment we chose water immersion, but I do believe thermocycling will more closely mimic clinical stresses on a denture liner and may be of more value to a prosthodontist. Conversely as previously discussed concomitant shearing or tensile bond strength tests should be run along with peel strength tests.

If water immersion is to be undertaken, then longer periods than 10-days possibly of up to 6months should be considered to see what the effects are on commonly used soft reliners and when a state of equilibrium will be attained.

Another potential shortcoming of this study is that milled samples were created using a band saw to section samples into correct dimensions. As surface of the milled denture is affected by the size of the milling bur and milling orientation, it may be more clinically acceptable to mill the subtractive denture base samples to ensure reline procedures will be carried out on a surface that will mimic intaglio surface of milled dentures.

Future research

It has been previously so eloquently stated that "ability of resilient lining material to resist tearing will be of great practical importance in clinical durability of relined dentures" (Alcantara et al 2012). In recognition of this it must be added that newer research in resilient liners may focus on developing newer compliant plasticized acrylic liners with higher tear strengths.

This in-vitro study does not take into account patient factors like denture hygiene and age of prosthesis. As we know, bonding to an older denture may be affected due to microbial colonization and mercaptan production, this study should be replicated with denture samples mimicking wear and microbial colonization for more clinical applicability.

Finally, we only tested one type of dental base polymer and dental liner polymer and their peel bond strengths. Research should also be focused on newer long term printed denture materials available in the market and interactions of different other brands of reline materials with them.

Chapter 5

Conclusions

The results of this study highlight that type of denture base and the 10-day water storage had no significant effect on the peel bond strength values of Coe Soft and Sofreliner Tough S. Whereas the type of reline material did significantly affect the peel bond strength.

Type of denture base significantly affected peel bond strengths of Coe Comfort with ProBase Hot showing highest values while Denture Base RP showed lowest strength values.

There may be generalised trend for reduction in peel bond strength values with 10-day water immersion with Coe Soft and Coe Comfort, but Sofreliner Tough S did not show much change in bond strength values.

It was also noted that water sorption seems to exert a plasticizing effect on Coe Soft and Coe Comfort as a result of 10-day water storage.

Within the limitations of this study, the following conclusions can be drawn.

- Tokuyama Sofreliner Tough S has much higher peel bond strength as compared to Coe-Soft resilient liner.
- Peel bond strength of Tokuyama Sofreliner Tough S, Coe Soft is not affected by manufacturing methods employed for denture bases. While bond strength of and Coe Comfort is significantly affected by manufacturing method of denture bases.
- Water sorption seems to reduce peel bond strength values except for Sofreliner Tough S.

Hypotheses Revisited

H01: Plasticized acrylic reline materials will not be different in terms of peel bond strength from silicone reline materials in relation to conventional, additive, and subtractive manufactured denture bases.

- Type of reline material significantly affected peel bond strength with Sofreliner Tough S showing much higher peel bond strength as compared to Coe-Soft resilient liner.
- **Null hypothesis rejected**

H02: Manufacturing method of denture base resin will have no effect on peel bond strength of plasticized acrylic-based denture-liner materials, silicone-based denture-liner materials, or tissue conditioner material.

- Type of denture base (which based on manufacturing technique was either conventional, subtractive, additive) had no significant effect on peel bond strength of Sofreliner Tough S and Coe Soft. While Coe Comfort had statistically significant different peel bond strength with different denture bases.
- **Null hypothesis is partially accepted.**

H2: Water immersion will have no effect on durability of the bond.

- 10-day water storage had no significant effect on the peel bond strength values of Sofreliner Tough S and Coe Soft. Coe Comfort showed significant difference in peel bond strength after 10-day water immersion.
- **Null hypothesis is partially accepted.**

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Appendix

Title: A comparative in-vitro analysis of peel bond strengths of chair side resilient reline materials to conventional, additive, and subtractive manufactured denture bases.

Running Title: Peel Bond Strength of Resilient Liners

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A comparative in-vitro analysis of peel bond strengths of chair side resilient reline materials to conventional, additive, and subtractive manufactured denture bases.

Purpose: To analyze peel bond strengths between three different denture bases and different classes of resilient reline materials.

Methods: Acrylic denture base samples were fabricated using heat cured PMMA (ProBase Hot; Lot No. Powder- YB1VHX, Liquid- Z01H18; Ivoclar Vivadent, Schaan, Liechtenstein); according to manufacturer's instructions in a custom fabricated stainless-steel mould to create rectangular acrylic blocks of 65 ×10 × 3mm. Subtractive CAD/ CAM denture base samples were created using a band saw by sectioning prepolymerized PMMA pucks (IvoBase CAD; Lot No. YB3KF9; Ivoclar Vivadent, Schaan, Liechtenstein) in test sample dimensions. For additive CAD/CAM denture base samples, first a prototype sample was designed using a free CAD software program (Meshmixer, Autodesk, Mill Valley, California, USA) and then 3D printed with a Form 3B printer (Formlabs Inc., Somerville, MA, USA), using a photopolymerizable denture base resin (Denture base RP; Lot No. BF19J21R; DENTCA Inc., Torrance, CA, USA). Post processing of 3D printed samples was carried out as per manufacturer's recommendations. Test surfaces were prepared following a standardised protocol of polishing and washing. These samples were then relined with silicone-based liner (Tokuyama Sofreliner Tough S; Lot No. 235E71; Tokuyama Dental Co, Tokyo, Japan)) and a plasticized acrylic liner (Coe Soft; Lot No. 2109141; GC labs, Alsip, USA). It was ensured that bonding was limited to only 22 mm of prepared test surface while remaining 43 mm of sample surface was left unbonded to allow peeling during testing. Samples were loaded into a Landmark® Servohydraulic testing machine and then peeled at crosshead speeds of 20 mm/min for resilient liners, until failure occurred.

Results: Results of this study show, that type of denture base (P value = 0.527) and the 10-day water storage (P value = 0.580) had no significant effect on the peel bond strength values of resilient liners. Type of resilient liner did significantly affect the peel bond strength (P value = 0). Sofreliner Tough S (Mean 1.645 ± 0.176 MPa) had significantly higher bond strengths than Coe Soft (Mean 0.2 ± 0.107 MPa).

<u>Conclusion</u>: Tokuyama Sofreliner Tough S has much higher peel bond strength as compared to Coe-Soft resilient liner. Peel bond strengths of Coe Soft and Sofreliner Tough S are not significantly affected by type of denture base and 10- day water immersion.

KEYWORDS: Resilient Denture Liners, Additive and Subtractive Denture Base

Introduction:

Complete edentulism is a highly prevalent oral disease worldwide and complete dentures have been a traditional and a common choice to treat edentulism [1]. There has been a steady decline in prevalence of complete edentulism mainly due to increased awareness, accessibility to oral health care and advent in preventive care but this decline is partially offset with increase in population [2]. Thus, it has been estimated there will be tens of millions of newly edentulous people requiring complete denture therapy in US by 2050 [3].

Conventional denture fabrication procedures utilize polymerization of polymethyl methacrylate (PMMA) into removable complete dentures. These conventional denture fabrication methods are well established, much researched, and have not changed in over 80 years [4]. There was however a paradigm shift with introduction of computer aided designing (CAD) and computer aided manufacturing (CAM) technologies in fabrication of conventional removable dental prosthesis (CRDP) by Maeda et al in 1994 [5]. Since their introduction, digital dentures have exploded in popularity. Purported benefits of CAD/CAM complete dentures over conventionally processed PMMA CRDPs include, but are not limited to: higher strength, lower distortion and much better mechanical properties with monolithic milled denture [6,7], reduced incidence of microbial colonization in milled denture bases [6,7], significantly increased denture retention in short term [10], significantly reduced number of post-delivery denture adjustment visits in first year [8,9,11] and reduced costs due to savings in chair and lab times [12]. Additionally, CAD/CAM denture fabrication could be achieved either through subtractive or additive manufacturing [9].

Denture base adaptation and good peripheral border seal have been described as some of the most important factors contributing to denture retention [13]. Soft tissue contours change throughout the life after tooth loss because of continued resorption of residual ridge [14,15]. This necessitates continuous alteration of intaglio surface of the complete removable dental prosthesis (CRDP) to maintain intimate contact with denture supporting tissues [13]. Refitting of the intaglio surface of the denture prosthesis to ensure continuous harmonious fit is thus a critical component of complete denture service [16]. This refitting can be easily achieved through a reline procedures. Relining involves additions to intaglio surface of an existing complete denture to refit the intaglio surface to the time dependent altered state of denture bearing tissues [16].

Resilient denture liners are most commonly available in 2 types: silicone based and plasticized acrylic-based resins, which can be either heat polymerized or auto polymerized [17]. Since acrylic-based liner resins have similar composition to the denture base resins they are expected to bond strongly without use of a primer or adhesive [18]. Silicone based reline materials have a different chemical composition to the denture base resins thus necessitate use of an adhesive to prevent frequent debonding [17].

Reline procedure does have its own set of multiple drawbacks with loss of adhesion being the most important and common reason for failure [18]. Various mechanisms have been proposed to increase bond strength between soft denture relining material and denture base material including use of a primer, adhesive or monomer application, acid etching, application of organic solvents like acetone or isobutyl methacrylate solution, silica coating, application of Er:YAG laser and oxygen plasma treatment [18, 19].

Various methods of testing mechanical properties of soft liners have been accepted in literature like tensile, shear and peel bond strength testing [20]. Peel testing has been proposed to be the best method for testing of bond strength between reline material and denture base [21].

There will be an expected ever-increasing demand of patients seeking complete denture treatment with CAD/CAM dentures providing an attractive and increasingly popular alternative to conventional dentures in future. Even with advent of implants, resilient liners with their multiple advantages and indications will keep on being needed and commonly utilized in removable prosthodontics. Thus, testing of the bonding interactions of these materials is a relevant topic for prosthodontic researcher.

The aim of this study is to determine and compare the peel bond strengths between plasticized acrylic resin-based long-term denture liner, silicone-based long-term denture liner and CAD/CAM denture bases (subtractive and additive) and conventionally manufactured PMMA denture base. A secondary aim of this study is to determine effects of 10-day water immersion on peel bond strength of these materials.

Materials and Methods:

In this in-vitro study, three different commercially available denture bases were studied: 1. conventional heat cured PMMA was ProBase Hot (Lot No. Powder- YB1VHX, Liquid- Z01H18; Ivoclar Vivadent, Schaan, Liechtenstein); 2. prepolymerized PMMA pucks were IvoBase CAD (Lot No. YB3KF9; Ivoclar Vivadent, Schaan, Liechtenstein); 3. photopolymerizable denture base resin was Denture base RP (Lot No. BF19J21R; DENTCA Inc., Torrance, CA, USA). These denture bases were relines with two different resilient denture liner materials: 1. RTV silicone-based long-term denture lining material was Sofreliner Tough S (Lot No. 235E71; Tokuyama Dental Co, Tokyo, Japan); 2. autopolymerizing plasticized acrylic-based long-term denture liner Coe Soft (Lot No. 2109141; GC labs, Alsip, USA). Peel bond strength of these relined dentures and effect of 10-day water immersion on peel bond strengths were evaluated.

ProBase Hot samples were fabricated in specialized stainless-steel moulds (with slots of inner dimensions of 65×10×3 mm to create test specimen of chosen dimension). Powder and liquid were measured in manufacturer recommended ratios and properly mixed. Probase Hot mix was packed in doughy stage into stainless-steel moulds under compression using manufacturer recommended “trial packing” method and processed overnight in a water bath. Moulds were allowed to bench cool before deflasking was undertaken. IvoBase CAD specimens were prepared by cutting pucks into test sample dimensions (65×10×3 mm) utilizing band saws. The external two layers from either side of the puck were discarded after sectioning to ensure that all the test samples had similar surface texture created by the band saw before surface preparation for testing. For additive CAD/CAM denture base samples, first a prototype sample in test dimensions was designed using a free CAD software program (Meshmixer, Autodesk, Mill Valley, California, USA) and exported as standard tessellation language (STL) data set. This STL was exported to the PreForm software (Formlabs Inc., Somerville, MA, USA) for optimized printing. A print orientation of 90° with a layer thickness set at 50 µm was utilized. 3D printing was performed with a Form 3B printer (Formlabs Inc., Somerville, MA, USA); using photopolymerizable Denture base RP; Lot No. BF19J21R; DENTCA Inc., Torrance, CA, USA). After printing, proper post processing was completed following manufacturer's recommendations using a Form Wash and Form Cure units (Formlabs Inc., Somerville, MA, USA). Post curing supports were removed using 0.3 mm sectioning discs (Komet USA LLC, Rock Hill, SC, USA).

Test surface preparation was achieved by scrubbing the denture base samples first with 1200 grit sandpaper discs and finally polishing with 400 grit emery paper (Norton Abrasives, Worcester, MA, USA). After preparation, all samples were first scrubbed with soap and a denture brush and then rinsed under running tap water for 20 seconds. Finally, these samples were additionally cleaned in an ultrasonic bath with distilled water for 20 minutes. Based on availability of the laboratory time for testing, these prepared denture samples were stored in distilled water at room temperature for 7-days before relining procedures were undertaken. all the prepared samples were allowed to air dry for at least 5 minutes at room temperature.

Only one-third length (approximately 22 mm) of the test sample would be bonded to denture base and two-third length (approximately 43 mm) would be left non- bonded. This was done to generate a peeling force during testing at the bonding interface. A blue pencil mark was drawn on prepared surface of all the samples to help envision demarcation between bonded and non-bonded lengths of the denture base samples. For samples receiving silicone-based long-term denture liner, a compatible bonding agent that is supplied by the manufacturer along with the Sofreliner Tough S kit was utilized (Sofreliner Tough S, Lot No. 235E71; Tokuyama Dental Co, Tokyo, Japan). Adhesive was applied to only the 22 mm length of the test sample that was to be bonded and allowed to air dry. Every effort was made to limit the spread of silicone adhesive and confine it to the areas being bonded only. For samples receiving plasticized acrylic-based long-term denture liner and tissue conditioner, no other adhesive was applied to the prepared test surface.

Non-bonded areas on all the samples were carefully coated with a very thin layer of lubricant supplied by the manufacturer, along with the Coe Soft resilient liner kit (Coe Soft, Lot No. 2109141; GC labs, Alsip, USA) and allowed to air dry.

Sofreliner Tough S was injected into each slot in the standardised stainless-steel mould, the area to be non-bonded was identified by previously drawn pencil mark on the mould and then reline material in this non-bonded region of the mould was covered with a polystyrene strip. Test sample was inverted carefully on to each slot with prepared surface towards the liner material ensuring only adhesive applied bonding area was allowed to be in contact with the liner and lubricated surface was ensured to be in contact with the polystyrene strip. A glass slab of approximately 500mg in weight was placed on this assembly and held in place with light finger pressure for 5 minutes. Coe Soft was properly measured and then powder and liquid were carefully mixed following manufacturer's instructions. Next each slot in the stainless-steel mould was filled with the reline material and then same steps as silicone liner were followed to create Coe Soft lined test samples.

After separation from the moulds, overlying excess liner material was trimmed with sharp knives and blades to match the underlying denture samples. This was done to ensure that all the test samples had a uniform unstretched length and width of the liner material before stretch test was initiated.

Lined denture base samples were loaded on a Landmark® Servohydraulic Test System (MTS Systems, Eden Prairie, MN, USA) and peeled till failure occurred. In each denture base groups sample numbers 1-5 were tested for peel bond strengths same day after relining procedures were undertaken. Sample numbers

6-10 were relined and then subjected to aging by immersion in distilled water for 10 days at room temperature.

Load (N) at which failure occured was recorded, similarly stretched length of the liner at the time of failure was measured using an electric ruler.

$$Ps = F \times W^{-1} \left[\frac{1 + (1 + E)}{2} \right]$$

Here F is applied force at which failure occurred, W is the width of specimen in peeling area, E is the extension ratio of material (ratio of stretched to unstretched lengths of the liner material).

3-way Analysis of Variance testing (ANOVA) was performed to determine whether statistical differences exist between materials and water immersion. A Tukey Test and Levene’s test was performed. All data was analyzed at a 0.05 level of significance using OriginLab (v. 2019b; OriginLab Corp, MA, USA).

Results:

Results of 3-way ANOVA test show, that type of denture base ($p = 0.5274$) and the 10-day water storage ($p = 0.5807$); had no significant effect on the peel bond strength values, whereas the type of reline material ($p = 0$), did significantly affect the peel bond strength. Interactions between reline material and storage ($p =0.4118$) were not statistically significant. Interactions between reline material and denture base ($p >0.001$), denture base and storage ($p = 0.0215$) and reline material, denture base and storage ($p = 0.0035$); were all statistically significant.

Results show that overall peel bond strength values were significantly higher for Tokuyama Sofreliner Tough S (Mean 1.645 ± 0.176 MPa) as compared to Coe Soft (Mean 0.200 ± 0.107 MPa); irrespective of denture base type or 10-day water storage.

Results show that, overall peel bond strength values of Coe Soft were highest for Formlabs Denture Base RP (Mean 0.256 ± 0.077 MPa), followed by IvoBase CAD (Mean 0.246 ±0.101 MPa), and lowest for ProBase Hot (Mean 0.101 ± 0.0607 MPa). These differences were statistically significant.

Overall peel bond strength values for Tokuyama Sofreliner Tough S were highest with ProBase Hot (Mean 1.751 ± 0.192 MPa), followed by Formlabs Denture Base RP (Mean 1.627 ± 0.147 MPa), and lowest for IvoBase CAD (Mean 1.555 ± 0.139 MPa). These differences were statistically significant.

Results show that there may be a trend for reduction in peel bond strength values with 10-day water immersion of Coe Soft while Sofreliner Tough S was not affected. Overall peel bond strength for Coe Soft lined samples at 0 days (Mean 0.225 ± 0.090 MPa) reduced after 10-days of water immersion (Mean 0.180 ± 0.116 MPa); these differences were not statically significant. Overall peel bond for Sofreline Tough S lined samples at 0-days (Mean 1.641 ± 0.252 MPa) was similar after 10-days of water immersion (Mean 1.648 ± 0.077 MPa); these differences were not statistically significant.

Discussion:

Loss of adhesion between the denture base and the reline material is the most important denture liner failure [18] and a common reason for failure of soft relined dentures [22].

Results show that overall peel bond strength values were significantly higher for Tokuyama Sofreliner Tough S (Mean 1.645 ± 0.176 MPa) as compared to Coe Soft (Mean 0.200 ± 0.107 MPa); irrespective of denture base type or 10-day water storage. This result is consistent with another recent study comparing peel bond strength of silicone denture liner with plasticized acrylic denture liner. It was found that the silicone-based liner had significantly higher average maximum bond strengths achieved during the peel test [23].

Results of our study also showed that type of denture bases on its own did not lead to significant difference in peel bond strengths ($p = 0.5274$). However, significant interactions were noticed on analysis between different tested denture bases and both Sofreliner Tough S and Coe Soft ($p < 0.05$). Our results are consistent with another study that concluded that type of denture base polymer and denture reline polymers affected the bond strength between them [24].

A mutual solubility or compatibility of the denture base polymer and the overlying liner polymer is essential to establish a durable bond [25]. Difference in chemical composition of silicone-based long-term denture liners than most PMMA based dentures has resulted in bond strengths of silicone-based long-term denture liners being considered inferior to plasticized acrylic-based long-term denture liners [26, 27].

A compatible manufacturer recommended adhesive was used, in our present study, with Sofreliner Tough S to ensure a good bond with the test denture specimens. It can be postulated that the adhesive provided with Sofreliner Tough S may have contributed to its higher peel bond strength in our testing. This inference agrees with conclusion of another study that mode of adhesive failure is affected by the choice adhesive employed [28].

For in-vitro testing, use of aging methods like water immersion aging which will cause hydrolysis of bonding interface has been suggested [29]. Results show that 10-day water immersion on its own led to statistically insignificant changes in peel bond strength values of both Coe Soft and Tokuyama Sofreliner Tough S ($p = 0.411$). However, interactions between these liners, type of denture bases and 10-day water immersion were statistically significant ($p < 0.05$). This finding partially concurs with study on rupture properties of denture soft lining materials. It was concluded that water immersion for 6-months deteriorated bond strength of all denture liner materials [30].

In our present study, majority of bonding failures were observed to be cohesive in nature with fracture of resilient liner materials being common observation. This is in general agreement with most of the previously conducted studies on peel bond strength. Most of the studies utilizing this method of testing peel bond strength noticed predominantly cohesive failure of denture liner samples [26, 31-34]. It has been suggested that cohesive failures in resilient liner materials during peel bond testing should be termed as “strength failure” rather than “bond failure” [33].

One limitation of the study was lack of thermocycling and if water immersion is to be undertaken, then longer periods than 10-days possibly of up to 6months should be considered. Another potential shortcoming of this study is that milled samples were created using a band saw to section samples into correct dimensions. As surface of the milled denture is affected by the size of the milling bur and milling orientation, it may be more clinically acceptable to mill the subtractive denture base samples to ensure reline procedures will be carried out on a surface that will mimic intaglio surface of milled dentures.

Conclusion:

The results of this study highlight that type of denture base and the 10-day water storage had no significant effect on the peel bond strength values of Coe Soft and Sofreliner Tough S. Whereas the type of reline material did significantly affect the peel bond strength.

Within the limitations of this study, the following conclusions can be drawn.

- Tokuyama Sofreliner Tough S has much higher peel bond strength as compared to Coe-Soft resilient liner.
- Peel bond strength of Tokuyama Sofreliner Tough S, Coe Soft is not affected by manufacturing methods employed for denture bases.
- 10 days water immersion seems to reduce peel bond strength values for Coe Soft but not for Sofreliner Tough S.

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Figures and Tables:

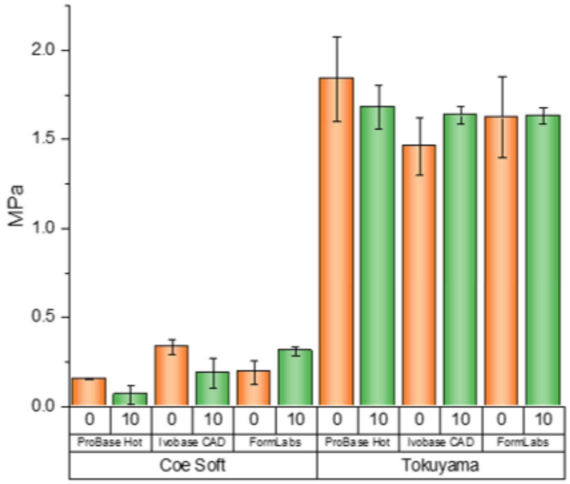
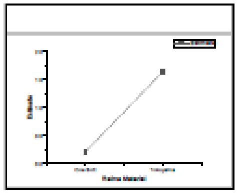
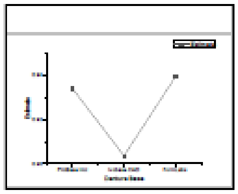


Figure 1. Graphical Representation of Mean and Standard Deviation for Peel Bond Strength Values of Coe Soft and Sofreliner Tough S with different Denture Bases at 0-days and 10-days

Reline Material



Denture Base



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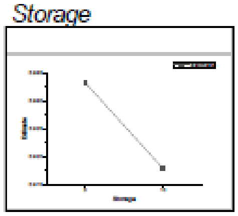
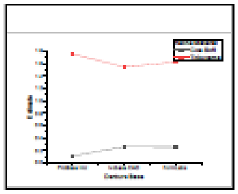


*Reline Material * Dentur*



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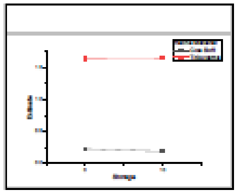

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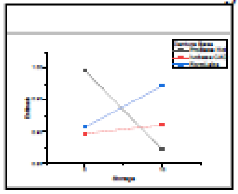

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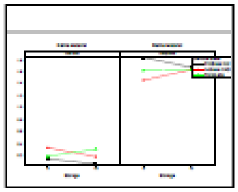
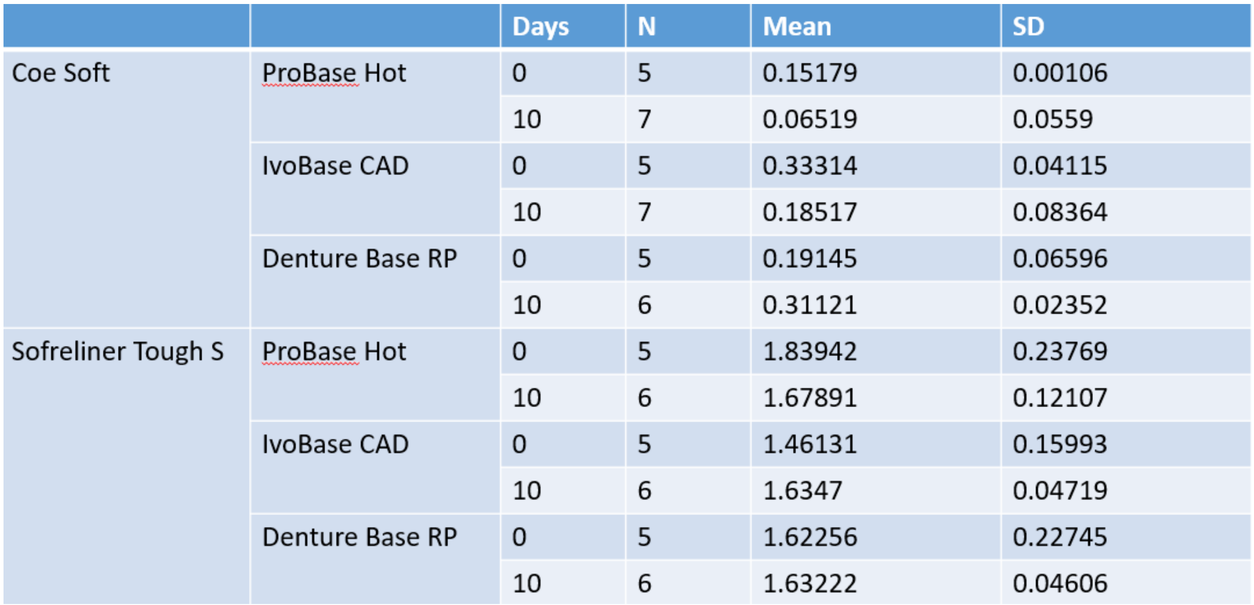


Figure 2. Graphic representation of 3-way ANOVA data

Table 1. Raw Data of Peel Bond Strength Values for All Samples Tested Listed in MPa



		Days	N	Mean	SD
Coe Soft	ProBase Hot	0	5	0.15179	0.00106
		10	7	0.06519	0.0559
	IvoBase CAD	0	5	0.33314	0.04115
		10	7	0.18517	0.08364
	Denture Base RP	0	5	0.19145	0.06596
		10	6	0.31121	0.02352
Sofreliner Tough S	ProBase Hot	0	5	1.83942	0.23769
		10	6	1.67891	0.12107
	IvoBase CAD	0	5	1.46131	0.15993
		10	6	1.6347	0.04719
	Denture Base RP	0	5	1.62256	0.22745
		10	6	1.63222	0.04606