COMPARISON OF DENTURE BASE ADAPTATION OF RAPID HEAT-CURED RESIN ACRYLIC USING DIFFERENT COOLING METHODS

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COMPARISON OF DENTURE BASE ADAPTATION OF RAPID HEAT-CURED RESIN ACRYLIC USING DIFFERENT COOLING METHODS

ABSTRACT

Introduction: 20 minutes rapid heat-cured resin acrylic is one of the denture base material improvisation to reduce processing time. Besides minimising polymerization shrinkage, cooling method plays an important role in producing denture base with good adaptation, leading to better treatment outcome.

Aim: The purpose of this study is to investigate the effect of different cooling methods on denture base adaptation of rapid heat-cured resin acrylic.

Materials and methods: Acron Express (Kemdent, UK) and Fast Heat Curing Acrylic (Huge Dent, China) are the resins used in this study. Both materials are 20 minutes heat-cured acrylic. In the present study, denture base adaptation of Fast Heat Curing Acrylic was compared with ISO 20795-1:2013 certified Acron Express when both were cooled down following manufacturer's instructions. On the other hand, comparison was done when Fast Heat Curing Acrylic was subjected to different cooling methods, namely the bench cooling and rapid cooling groups. Forty maxillary edentulous stone cast were duplicated from silicone mould (eight for each specimen groups). Putty index was used to produce denture base with standardized thickness. One master stone cast was scanned prior to fabrication process. Denture bases fabricated according to assigned groups were hydrated for 24 hours prior to scanning with 3Shape E1 laboratory scanner. The scanned Standard Tessellation Language (STL) file for each denture base was superimposed on the scanned STL file of maxillary edentulous stone cast using Materialise 3-matic software. Mean of root mean square (RMS) value and interquartile range (IQR) of overall numeric distance measurements were obtained to analyse accuracy and reproducibility of different specimen groups. Welch's and two way analysis of variance were used to evaluate the differences between different material and cooling methods (α=0.5).

Results: Fast Heat Curing Acrylic has lower RMS mean and narrower interquartile range than Acron Express when cooled down according to manufacturer's instructions. No statistically significant difference in denture adaptation of Fast Heat Curing Acrylic when subject to different cooling methods.

Conclusion: These results suggested Fast Heat Cure Acrylic is comparable to Acron Express when cool down according to manufacturer's instructions. Although bench cooling is advocated when processing denture base with Fast Heat Curing Acrylic, rapid cooling is a viable alternative especially when shorter processing time is needed during community service.

Keywords: denture base adaptation, cooling methods

PERBANDINGAN ADAPTASI PLAT GIGI PALSU PENUH ANTARA *RAPID HEAT CURED ACRYLIC* DENGAN KAEDAH PEYEJUKAN YANG BERBEZA

ABSTRAK

Pengenalan: 20 minit *rapid heat cure acrylic* dihasilkan untuk mengurangkan masa memproses gigi palsu. Selain cara polimerasi, kaedah penyejukan merupakan salah satu faktor utama untuk menghasilkan gigi palsu dengan adaptasi yang baik.. Ini adalah penting untuk meningkatkan kualiti kehidupan pesakit yang telah kehilangan semua gigi. **Tujuan;** Tujuan kajian ini adalah untuk mengkaji selidik kesan kaedah penyejukan yang berbeza dalam adaptasi gigi palsu yang diproses dengan *rapid heat cured resin acrylic*. **Bahan dan kaedah:** Bahan-bahan yang digunakan dalam kajian ini adalah *Acron Express* dan *Fast Heat Curing Acrylic*. Kedua-dua bahan terlibat adalah *20 minutes heat cured acrylic*. Ketepatan dimensi bahan tersebut merupakan salah satu faktor penting untuk menghasilkan plat gigi palsu yang beradaptasi baik bila dipakai oleh pesakit. Dalam kajian ini, adaptasi gigi palsu yang diproses dengan *Fast Heat Curing Acrylic* dibandingkan dengan *Acron Express* yang mempunyai sijil ISO 20795-1: 2013 apabila kedua-dua bahan disejukkan ke suhu bilik dengan mematuhi arahan pihak kilang. Selain itu, perbandingan telah dilakukan apabila *Fast Heat Curing Acrylic* tertakluk kepada kaedah penyejukan yang berbeza, iaitu *bench cooling* dan *rapid cooling*. Sejumlah 40 model gigi palsu penuh rahang atas telah disediakan dengan menggunakan acuan silikon (8 untuk setiap kumpulan). *Putty index* telah digunakan untuk menghasilkan plat gigi palsu dengan ketebalan seragam. Model *edentulous* rahang atas kemudiannya diimbas sebelum proses fabrikasi spesimen. Plat gigi palsu penuh yang dibuat berdasarkan kumpulan yang ditetapkan disimpan dalam air tidak melebihi 24 jam sebelum diimbas dengan *3Shape E1 scanner*. STL fail plat gigi palsu penuh yang telah diimbas, disuperimposisikan dengan model *edentulous* rahang atas menggunakan *Materialize 3-matic software*. Nilai min *root mean square value* dan *interquartile range (IQR) of overall*

numeric distance measurements dicatat untuk menganalisis ketepatan dan *reproducibility* kumpulan spesimen yang berbeza. Analisis Welch dan *two way analysis of variance* telah digunakan untuk menilai perbezaan antara bahan dan kaedah penyejukan yang berbeza (α=0.5).

Keputusan: Analisis data telah menunjukkan bahawa *Fast Heat Curing Acrylic* lebih *reproducible* berbanding dengan *Acron Express* apabila disejukkan mengikut arahan pihak kilang. Walau bagaimanapun, tiada perbezaan yang ketara didapati dari segi ketepatan secara keseluruhan. Selain itu, tiada perbezaan statistik yang signifikan dari segi adaptasi plat gigi palsu penuh apabila diproses dengan Fast Heat Curing Acrylic dengan kaedah penyejukan yang berbeza.

Kesimpulan: Keputusan ini mencadangkan *Fast Heat Curing Acrylic* adalah setanding dengan *Acron Express* apabila disejuk mengikut arahan pihak kilang. Walaupun *bench cooling* dicadangkan semasa pemprosesan plat gigi palsu dengan *Fast Heat Curing Acrylic*, *rapid cooling* adalah alternatif yang sahih terutamanya apabila peuntukan masa yang singkat semasa program bakti masyarakat terutamanya di kawasan pedalaman.

Kata kunci: adaptasi gigi palsu, kaedah penyejukan.

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LIST OF SYMBOLS AND ABBREVIATIONS

ANOVA	:	Analysis of Variance
CTE	:	Coefficients of Thermal Expansion
FTIR	:	Fourier-transform Infrared Spectroscopy
M	:	Mean
IQE	:	Interquartile Range
RMS	:	Root Mean Square
SD	:	Standard Deviation
STL	:	Standard Tessellation Language
Tg	:	Transition Temperature
UK	:	United Kingdom

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CHAPTER 1: INTRODUCTION

Acrylic resin or "polymethylacrylate" (PMMA) was introduced in 1940s, commonly used to fabricate removable prostheses due to its favourable working characteristic, excellent aesthetics, adequate mechanical strength and comparatively inexpensive. In order to reduce the time needed to deliver a removable prosthesis, there has been continuous development on this material. Studies showed there are no significant dimensional changes between acrylic resin produced by long or rapid curing cycle (Firtell et al., 1981; Negreiros et al., 2009). This is in accordance to the 5 years clinical study done by Polychronakis et al. in 2003.

Besides curing cycles, cooling methods play a significant role in dimensional accuracies of a removable prosthesis. Many literatures suggested bench cooling or gradual cooling after processing heat-cured acrylic is effective in minimizing dimensional changes of the prosthesis (R. L. Consani et al., 2006; Kimoto et al., 2005). This is because residual internal stress created during heat processing is relaxed in the stone mould with longer cooling period, thereby reducing warpage during deflasking (Kimoto et al., 2005).

However, gradual cooling or bench cooling method is time consuming. The ability of laboratory to rapidly process the acrylic resin dentures offers potential benefit in terms of both time and expense for both technician and clinician. Especially in community setting, whereby with shorter processing time, the clinicians can see more patients and cater for their prosthodontic needs. Although Computer-aided design and computer-aided manufacturing (CAD CAM) denture was found to be most reproducible with shortest delivery time, it is far more expensive, technically sensitive and not readily available in developing countries (Goodacre et al., 2016). Hence, it is important to ascertain whether sufficient accuracy with good denture base adaptation can be achieved by shorter cooling period which is more practical in our daily setting. To date, there has been no study done

on the effect of different cooling intervals on denture base adaptation of 20-minutes-cured acrylic.

1.1 The null hypothesis of the research

1. There is no difference in denture base adaptation of Acron Express (Kemdent, UK) and Fast Heat Curing (Huge Dent, China) denture base when cooling according to manufacturer instructions.
2. There is no difference in denture base adaptation of Fast Heat Curing (Huge Dent, China) denture base when cooling according to manufacturer instructions and other different cooling methods.
3. There is no differences in denture base adaptations of Fast Heat Curing (Huge Dent, China) denture base at different locations when cool down with different methods.

1.2 The aim of research

The aim of this study is to investigate the effect of different cooling methods on the denture base adaptation of two commercially available 20-minute-heat-cured acrylic.

1.3 Objectives of the research

An *in vitro*/ laboratory study was conducted:

1. To compare denture base adaptation of two commercially available 20-minutes heat-cured acrylic; Fast Heat Curing (Huge Dent, China) with Acron Express (Kemdent, UK) when cooling according to manufacturer's instructions.
2. To assess effects of different cooling methods on denture base adaptation of 20-minutes-heat-cured-acrylic; Fast Heat Curing (Huge Dent, China).
3. To explore the effect of different cooling methods on denture base adaptation of 20-minutes-heat-cured-acrylic. Fast Heat Curing (Huge Dent, China) at different locations.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Acrylic resin polymer was first introduced in mid-1940s, commonly used for fabricating denture due to its favourable working characteristic, excellent aesthetics, adequate mechanical strength and inexpensive (Anusavice, Shen, et al., 2013; Peyton, 1975). In order to fabricate a comfortable and fitting denture, it should be dimensionally stable with good adaptation and border seal (Ono et al., 2004). However, shrinkage and expansion of the material during processing procedures are virtually inevitable, leading to development of new processing methods and materials (R. Consani et al., 2002; Murray & Darvell, 1993; Woelfel et al., 1960).

2.1.1 History of denture base material

Earliest denture base material was documented before year 1900. Prior to development of plastic material, replacement of missing tooth was dependent on natural resins or exudates and tissues from plants, animals and insects (Johnson, 1959). For example, shellac material, hardwood, ivory or bone and fastened to natural teeth by screws or other means before 1800 (Guerini, 1969). However, the dentures were functionally ineffective, easily stained, pitted, and foul from decay (Peyton, 1975). Despite more discoveries in late 1800s such as natural rubber (Johnson, 1959), vulcanite (Winkler & Vernon, 1978), celluloid (Sweeney, 1939), epoxy resin (Kydd & Wykhuis, 1958), none of these materials were able to produce dimensionally stable and accurate denture until the introduction of a heat processed thermosetting material, polymethyl-methacrylate (PMMA) in 1936 (Kimball, 1938; Peyton, 1950).

It was estimated that by 1946, 96 % of the denture were made of PMMA because of its favourable working characteristics, inexpensive and easy to manipulate. Furthermore, it has adequate strength, biocompatible with better aesthetic (Leong & Harcourt, 1974;

Peyton, 1975). Despite all the excellent properties of PMMA, one of the drawbacks is dimensional changes due to shrinkage and expansion during processing (Skinner & Cooper, 1943). This has led to the improvisation of PMMA compositions, manipulation techniques as well as processing methods.

2.1.2 Criteria for an ideal denture base material

In order to fabricate a retentive and comfortable denture, material of which the denture base is constructed must have certain requirements to perform satisfactorily. From the perspective of both the dentist and technician, the material should be of adequate strength to withstand occlusal loading, easy to manipulate, low toxicity during processing, biocompatible with oral cavity, dimensionally stable, radiopaque and easy to repair (Bonsor & Pearson, 2012).

On the other hand, from the patient's view point the denture should fit well and be comfortable in use, does not traumatize the tissues, easy to clean, aesthetically pleasing both immediately on placement and in the longer term, allow good heat diffusion to retain normal perception of thermal stimuli and permit food to be tested normally so that food can be appealing (Bonsor & Pearson, 2012).

Despite the continuous improvisation of the current denture base materials, none of the material fulfil all the ideal criteria. The materials which full filled most of these criteria are the resin polymers, namely polymethyl methacrylate (PMMA). For this reason, many researches have been focusing on the properties and development in every aspects of acrylic resin since the early 20th century till now.

2.2 Physical and mechanical properties of acrylic resins

The physical and mechanical properties of acrylic resins are important to produce a fitting, comfortable and functional removable partial denture. Some of the minimal requirements are set out in ISO specification 20795-1:2013 as shown in (Table 2.1).

Table 2.1: Requirements of denture base polymers (ISO, 2013).

Type	Ultimate Flexural Strength	Flexural Modulus	Residual Methyl Methacrylate Monomer	Water Sorption	Solubility
	MPa (minimum)	MPa (minimum)	Percent mass fraction (maximum)	µg/mm³ (maximum)	µg/mm³ (maximum)
1,3,4,5	65	2000	2.2	32	1.6
2 (auto-polymerize)	60	1500	4.5	32	8

2.2.1 Polymerization shrinkage

Polymerization shrinkage contributes to most of the dimensional inaccuracies in denture base acrylic (Anthony & Peyton, 1962; Takamata et al., 1989). Density of the mass changes from 0.94 to 1.19 g/cm³ when methyl methacrylate monomer is polymerized to form polymethyl methacrylate which results in 21% volumetric shrinkage. Therefore, when a heat cured acrylic resin is mixed as suggested powder to liquid ratio, only about one third of the mass is liquid monomer. The remainder of the mass is prepolymerized PMMA. As a result, the volumetric shrinkage exhibited by the polymerized mass should be around 5-9 % (J. F. McCabe & Walls, 2013; O'Brien, 2008; Van Noort & Barbour, 2014), thus with an average value of 7% (Anusavice, Shen, et al., 2013; Grant, 1978). According to the projected volumetric shrinkage of 7%, an acrylic resin denture base should exhibit a linear shrinkage around 2%. But in reality, linear shrinkage rarely exceeds 1% (Anusavice, Shen, et al., 2013).

2.2.2 Porosity

Porosity is one of the undesirable characteristics of PMMA as it compromises the physical, aesthetic and hygienic properties of a processed denture base. Gettleman et al., 1997 reported the tensile strength of porous acrylic resin is 1/6 to 1/8 to dense PMMA (Gettleman et al., 1977). Depending on curing condition, porosity above 11% is associated with deteriorate mechanical properties and aesthetics (Keller & Lautenschalger, 1985). Generally, porosity can be classified as gaseous porosity, contraction porosity and porosity caused by inadequate mixing of the powder liquid components (Anusavice, Phillips, et al., 2013; Keller & Lautenschalger, 1985).

2.2.3 Water absorption and solubility

The absorption of water by denture base resin when placed in an aqueous environment exerts significant effects on the mechanical and dimensional properties of the processed denture (Hargreaves, 1978). As water forced the polymer chain apart, it causes slight expansion of the polymerized mass. On top of that, it may produce some effects such as reversible loosening or plasticization of the structure, in a way affecting the denture's durability (Garcia-Fierro & Aleman, 1982).

PMMA exhibits a water sorption value of 0.69mg/cm². For each 1% weight produced by water absorption, acrylic resin exhibits a linear expansion of 0.23%. Laboratory trials indicate that linear expansion caused by water absorption is approximately equal to the polymerization shrinkage during denture fabrication. Therefore, these processes offset one another. On the other hand, Jagger (1978) reported if residual monomer is present, less monomer conversion occurs and may result in increased sorption and solubility (Jagger, 1978). Some copolymers such as those containing hydroxyethyl methacrylate has higher water sorption than traditional PMMA but overall a typical acrylic denture base might take 17 days to become fully saturated with water (Powers & Wataha, 2013).

Although denture base is soluble in a variety of liquids, they are virtually insoluble in fluids commonly found in the oral cavity. According to American Dental Association (ADA) specification No. 12, weight loss of denture base resin after water immersion must not be greater than 0.04mg/cm². Although such a loss is negligible from clinical perspective, acrylic which have low solubility but release residual monomer may cause allergic reactions in some individuals, especially within first to two weeks of service (Pfeiffer & Rosenbauer, 2004).

2.3 Classification of denture base material

According to International Organization for Standardization (ISO) 20795-1:2013, denture base can be classified according to their composition and processing technique as shown in (Table 2.2).

Table 2.2: Classification of denture base material (ISO, 2013).

TYPE	CLASS	DESCRIPTION
1	1	Heat-polymerizable materials (Powder and liquid)
1	2	Heat-polymerizable materials (Plastic cake)
2	1	Autopolymerizable materials (Powder and liquid)
2	2	Autopolymerizable materials (Powder and liquid for pour-type resins)
3	-	Thermoplastic blank or powder
4	-	Light-activated materials
5	-	Microwave-cured material

Different types of denture base material are developed based on different clinical application. Acrylic resin or more specifically PMMA is a polymer formed from the addition reaction of the monomer methylmethacrylate (MMA). Even though PMMA is

available as gel, sheet or blank, the powder/liquid presentation is most widely used (Bonsor & Pearson, 2012; Gladwin & Bagby, 2017).

PMMA powder is composed mainly of small spheres called beads or pearls that may have be modified with small amounts of ethyl methacrylate or ethyl acrylate to produce a softer final product. The size of these particle is approximately 150 μm in those resin which are processed by heat. Benzyl peroxide is coated at the surface of polymer beads for the initiation of polymerization. As only a small amount of polymer is required to start the reaction, it is important that these beads are not contaminated to prevent premature initiation of polymerization reaction. PMMA is a clear, glass like polymer to which pigments and opacifiers have been incorporated in order to produce a more natural coloured denture base (Chaing, 1984; Sakaguchi & Powers, 2012).

The liquid is predominantly non-polymerized methyl methacrylate monomer. It is a clear colourless, low viscosity liquid with a boiling point of 100.3ºC, melting point of -48ºC, highly inflammable and very susceptible to free radical addition polymerization. Therefore, with small amount of hydroquinone which is an inhibitor, it prevents undesirable polymerization or "setting" of the liquid during storage, hence prolonging its shelf life. Another way of reducing unwanted radicals is to store the liquid in a can or a dark brown bottle. On the other hand, glycol methacrylate which is a commonly used cross linking agent can be added to liquid at a concentration of 1-2% by volume to improve denture base's physical properties (J. F. McCabe & Walls, 2013; Van Noort & Barbour, 2014).

PMMA is formed by addition polymerization of multiple methyl methacrylate molecules in three stages (Figure 2.1) which is initiation, propagation and termination (Combe, 1992). In the presence of heat or chemical activation, benzyl peroxide as the initiator breaks down to free radicals. They act upon the vinyl group of methyl methacrylate, opening the double bond causing formation of a new single carbon bond.

This process is known as a free radical addition polymerization chain reaction resulting in the shift of the unshared electron to the end of the monomer and the formation of activated monomer molecules (Anusavice, Shen, et al., 2013; O'Brien, 2008).

Activated monomers attack the double bonds of additional available monomers, resulting in the rapid addition of monomer molecules to the free radical. The second stage, propagation, continues as the chain grows in length. Chain termination can occur at any time and is dependent upon the concentration of available free radicals resulting from the mutual reaction of two free radicals (Combe, 1992; O'Brien, 2008).

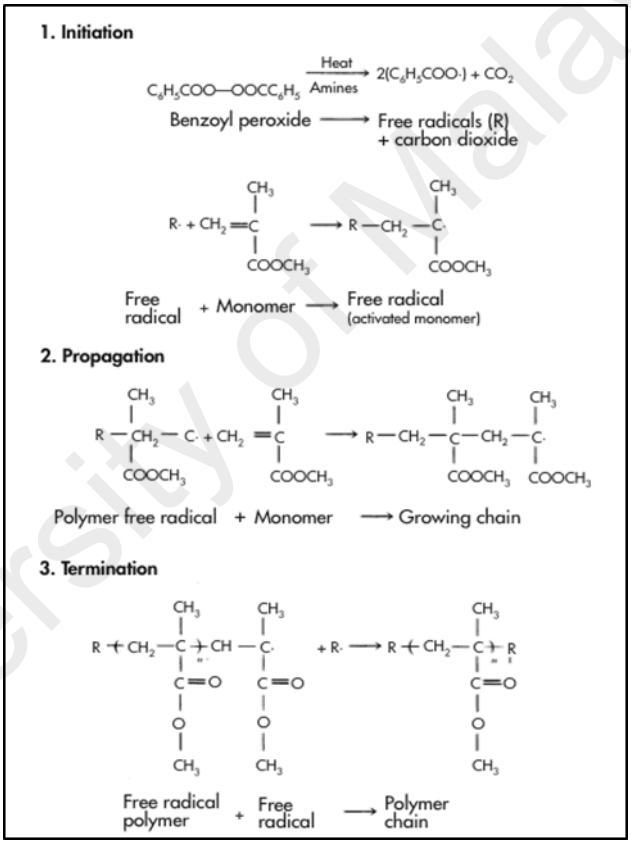


Figure 2.1: Three stages of addition polymerization of methyl methacrylate (O'Brien, 2008)

2.3.1 Heat curing polymer

The energy required for polymerization of heat activated PMMA is most commonly provided in the form of water bath, or less frequently a microwave oven (Arora et al., 2011; Lai et al., 2004). Benzoyl peroxide is commonly used as the initiator due to its low cost, when heated above 60ºC, molecules of benzoyl peroxide decompose, producing

pairs of free radicals which rapidly attacks the double bond in methyl methacrylate, initiating chain reaction (Powers & Wataha, 2013).

Clinically monomer and polymer are mixed together in a ratio of 1:3 by volume and goes through five distinct stage. During the first stage, also known as sandy stage, little or no interaction occurs on a molecular level, polymer beads remained unaltered. Next which is sticky stage, the monomer begins to penetrate the surface of individual particles causing the polymer chains to uncoil thereby increasing viscosity of the mix. Subsequently, the mass enters a doughlike stage where monomer and dissolved polymer are formed. However, it is important to note that a large quantity of swollen but undissolved polymer are remains. It is best to introduce the material into mould cavity at the latter phases of doughlike stage when it is no longer tacky or stick to spatula. Following the doughlike stage, the mixture enters rubbery or elastic stage. At this stage, monomer is dissipated by evaporation and by further penetration into remaining polymer beads. The mass rebounds and no longer flows freely hence cannot be moulded by conventional compress techniques (Anusavice, Phillips, et al., 2013; Ferracane, 2001).

2.3.2 Autopolymerized polymer

In 1947, chemical activators that initiated polymerization at room temperature were developed. Such acrylic resins also known as self-cured, chemically cured, cold cured or autopolymerized. They do not rely on heat to initiate their cure. Tertiary amine such as N,N dimethyl-para-toludine or sulphinic acid are commonly added to the monomer and decomposes benzoyl peroxide to produce sufficient free radicals on initiating polymerization (Bonsor & Pearson, 2012; Murray & Darvell, 1993).

The main difference between heat cured polymer and autopolymerized polymer is the method by which benzoyl peroxide is divided to produce free radicals. Otherwise all factors in the process such as initiator and reactants remain the same (J. F. McCabe &

Walls, 2013). The degree of polymerization achieved in autopolymerized polymer is usually less than heat cured resins (Mowery et al., 1958). This shows that there is a greater amount of unreacted monomer in denture bases fabricated via chemical activation which may lower the tensile strength, hardness, stiffness and fatigue resistance, mainly due to the plasticizing effect of the monomers (Honorez et al., 1989; Johnston et al., 1981). Furthermore resin polymerization via chemical activation generally display 3-5% free monomer, whereas heat activated resin exhibit 0.2-0.5% free monomer (Anusavice, Phillips, et al., 2013; Bonsor & Pearson, 2012). In relation to the previous statement, several literature reported that this high level of residual monomers was responsible for mucosal irritation, thereby compromising the biocompatibility of denture base (Doğan et al., 1995; Kostić et al., 2009; Pfeiffer & Rosenbauer, 2004).

As a result of less conversion of the monomer to polymer, autopolymerized polymer display slightly less shrinkage than heat-cured polymer (Mowery et al., 1958). This imparts less dimensional change on setting with only 0.1% dimensional change seen on polymerization (Bonsor & Pearson, 2012). On the other hand, autopolymerized polymer generally is inferior to the color stability of heat-cured polymer owing to the presence of tertiary amines which are susceptible to oxidation. Nonetheless discoloration of these resins can be minimized by the addition of stabilizing agents that prevent oxidation (Bohra et al., 2015).

2.3.3 Light activated material

First light activated material was developed in 1985 by Dentsply International Company under the name “Triad” (Al-Mulla et al., 1988). It is supplied in sheet and rope forms in a light proof pouch. This material is composed of urethane dimethacrylate (UDMA), microfine silica and high molecular weight acrylic resin monomer. The filler consists of varying sizes of acrylic-resin beads. Photosensitizing agent such as

camphorquinone serves as the initiator for polymerization while visible light acts as the activator (Anusavice, Phillips, et al., 2013).

2.3.4 Microwave cured material

Microwave cured denture base material was first introduced in 1968. Kimura and friends reported that it was possible to cure acrylic resin in a shorter time as compared to the conventional heat technique (Kimura et al., 1987). Microwaves are electromagnetic waves produced by a magnetron, causes the methyl methacrylate molecules within the acrylic resin to orient themselves in the electromagnetic field at a frequency of 2450MHz. Numerous polarized molecules are flipped over, leading to molecular fiction and produced heat which breaks down the bezoyl peroxide molecules into free radicals, initiating chain reactions (De Clerck, 1987). Therefore microwave activated polymerization is independent of thermal conductivity, curing cycles involving the application of rapid heat may be conducted without development of high exothermic temperature (Lai et al., 2004).

2.4 Processing methods for heat cured acrylic resins

2.4.1 Compression molding technique

Heat-cured denture bases are most commonly processed by the compression moulding, also known as conventional pressure packing technique. To allow processing of the acrylic, it is important to have an accurate wax trial denture prepared, subsequently sealed into master cast and flasked (Anusavice, Phillips, et al., 2013). By using boiling water and detergent, the wax is completely removed from flask investment. Next the master cast is coated with a thin layer of separating medium such as sodium alginate or ammonium alginate to prevent adherence of investment material (Combe, 1992; Grant, 1978).

The packing and adaptation of denture base resin within the mould cavity are termed packing. Is it important that the mould cavity is adequately filled to avoid excessive

thickness associated with tooth movement or noticeable voids (Anusavice, Phillips, et al., 2013). Furthermore, in order to prevent faults during packing, it should be carried out in a number of stages with gradual incremental pressure application. Application of a polythene separating sheet, trial closure, removal of excessive resin until no more flash is evident upon opening the denture flask. When flash is no longer apparent, the mould is closed for the last time with no polyethylene sheet placed. After that, the mould is properly aligned, placed in flask press and followed by flask carrier to maintain pressure on flask during denture base processing (Taylor, 1941).

The polymerization reaction is activated by immersing packed flask in hot water bath. As the reaction is very exothermic, and because the thermal conductivity of acrylic material is lower as compared to gypsum mold, there comes a point when more heat is being produced by the reaction than can be dissipated. As shown in (Figure 2.2) during the early stage, the flask and the dough are at lower temperature compared to external water bath. However, when it is around 70ºC, the reaction rate increased whereby internal temperature of acrylic may reach 130ºC or more, especially if the material is thick. As monomer has a boiling point only just over 100ºC, this might cause porosity and affects the strength of the produced denture base (Tuckfield, 1943). However, this can be overcome by controlling the heat of the flask, proper clamping during flasking or increases boiling point by increasing pressure during processing (Yau et al., 2002).

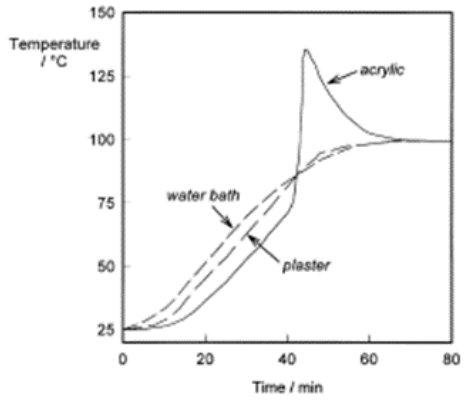


Figure 2.2: Changes of temperature observed in water bath, plaster and acrylic resins when a denture base is processed by raising the water bath continuously to 100˚C (Tuckfield, 1943).

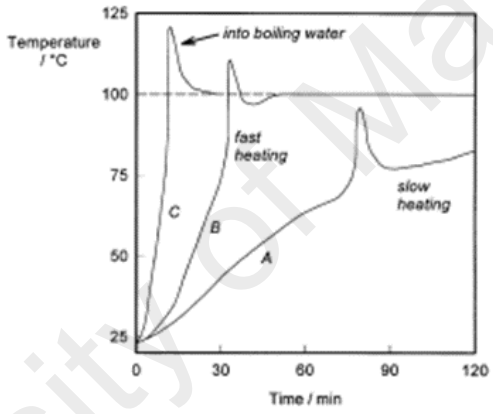


Figure 2.3: Temperature changes in acrylic resin when subjected to various curing schedules (Tuckfield, 1943).

(Figure 2.3) showing the relationship between the rate of heating and temperature rise within the denture base. As the boiling point of monomer is 100.8ºC, polymerization represented by curve C probably would produce porosity in thick portions of acrylic denture since the temperature is way above the boiling point. On the other hand, curve A represents a slow rate of heating which fails to reach the boiling temperature of the monomer, resulting higher level of unreacted monomer. Hence, an optimum polymerization cycle lies somewhere between curve A and C which is well represented by curve B (Tuckfield, 1943).

2.4.1.1 Long curing cycle

As low curing temperature prevents boiling of the monomer during exothermic reaction. A long curing cycle of 7 to 14 hour around 70ºC is used to cure the acrylic. Longer curing time would be needed to achieve a higher degree of polymerization since lesser radicals are produced in this decreased heating rate (Gürdal et al., 2000; Harrison & Huggett, 1992). However, Vallitu and colleague mentioned 70ºC is below the glass transition temperature of the polymer. Consequently, it does not only produced fewer radicals but also lower molecular motion for polymerization (Vallittu et al., 1998). On top of that, with the increased levels of residual monomers which acts as plasticizer, decreased transverse bond strength and surface hardness were reported in acrylic resins underwent this curing cycle (Arab et al., 1989).

In order to produce the best surface hardness and tensile strength, a second technique involves processing the denture base resin in a 74ºC water bath for 8 hours and then increasing the temperature to 100ºC for 1 hour (Jagger, 1978). This cycle allows higher degree of polymerization and removed most of the residual monomer at 100ºC (Harrison & Huggett, 1992).

2.4.1.2 Short cycle

First 20-minutes-heat-cured acrylic was reported by Firtell and colleagues in 1981. Austin and Becker mentioned short heat curing cycle ranging from 0.5 to 2 hours were frequently used in commercial dental laboratories due to its reduces processing time (Austin & Basker, 1982). However Jerolimov and friends claimed that short cycle has a potential risk of porosity especially at the thick sections of denture bases, owing to possible high exothermic reaction (Jerolimov et al., 1989).

Study found that a small amount of tertiary amine dimethyl-p-toluidine was added in most of the special rapid heat cure material. The concept was polymerization can begin

at a low rate after mixing so that the large exothermic reaction with sudden polymerization is avoided, thereby reducing porosity and much increased rate of polymerization. Furthermore, it was shown although rapid heat cured resins produced higher levels of residual monomer than conventional overnight cures, it is not enough to influence the mechanical properties (Jerolimov et al., 1989). Nevertheless, on the contrary, there are studies reported 20 minutes heat cure acrylic has lower Vickers hardness and impact strength compared to conventional heat cured acrylic (Farina et al., 2012; Uzun & Hersek, 2002). This is probably due to increased residual monomer which is directly proportional to the hardness value.

Negreiros and the team (2009) found dimensional stability of rapid polymerizing acrylic resin processed in boiling water for 20 minutes is comparable to the longer cycle (Negreiros et al., 2009). This supported the older articles which mentioned dimensional changes observed on the conventional and rapid heat cured resin did not differ much from each other during processing or up to 5 years follow up (Firtell et al., 1981; Polychronakis et al., 2003).

2.5 Different flask cooling methods

2.5.1 Rationale of flask cooling

Whenever a natural dimensional change is inhibited, the affected material sustained internal stress. If stresses are relaxed, distortion of the material can occur (Anusavice, Phillips, et al., 2013). Residual stresses produced in denture bases during processing are due to several interrelated phenomena. Firstly, internal stresses generated when denture base undergoes nonuniform volume changes as the acrylic polymerizes (K. M. Murphy et al., 1985). A second source of stresses produced when a polymerized resin is cooled down below its glass transition temperature, the resin becomes relatively rigid and further cooling results in thermal shrinkage. Lastly, since denture base resin is encased in a rigid

investing medium, difference of thermal expansion coefficient between two materials causes disparity in contraction rates thus yielding stresses within the resin (Anusavice et al., 2013; Mc Cabe & Wilson, 1980).

According to Mc Cabe and friends, it would be expected that the stresses generated by thermal contraction will be relieved shortly after denture has been removed from mould whereas the stress due to polymerization contraction will be relieved gradually. The reason of this observation is that the stresses of the thermal contraction are of instantaneous mechanical nature, whereby the stresses caused by polymerization shrinkage was relaxed by molecular orientation of the polymer (J. McCabe & Wilson, 1980). Thus, dimensional changes occurring shortly after removal of the denture from the mould will be mainly due to relaxation of thermal contraction stresses whilst continued long term deformation will be due mainly to relief of polymerization shrinkage.

In short, magnitude of dimensional change is strongly dependent on the cooling system. This is because the stress would be relaxed during the cooling process and the magnitude of the strain, developed by cooling is proportional to the temperature difference between the glass transition temperature of the resin and room temperature.

2.5.2 Types of flask cooling methods

Numerous studies have been conducted on the effects of different cooling methods on dimensional stability or accuracy of acrylic resin. In studies, they are generally being divided into: (1) Rapid group or quench cooling, (2) Bench cooling, (3) Slow cooling group (R. L. Consani et al., 2006; Kimoto et al., 2005; Savirmath & Mishra, 2016; Wong et al., 1999).

Many literatures reported linear changes is more in rapid group amongst the different cooling methods. Most of the residual stresses in processed denture are generated by the

difference in thermal contraction between the mould and acrylic resin during cooling (R. L. Consani et al., 2006; Ganzarolli et al., 2002; Kimoto et al., 2005; Savirmath & Mishra, 2016). Hence, in this group where the processed denture is subjected to rapid cooling, sudden change of temperature will cause an uneven thermal contraction in various part of denture base resin thereby inducing greater warpage or dimensional accuracies.

On the other hand, slow cooling either in water bath or bench cooling results in less dimensional change than rapid cooling (Ganzarolli et al., 2002; Kimoto et al., 2005). This is because residual internal stress in heat activated acrylic denture base was relaxed in the stone mould with longer interval of time after completion of cooling, thus dimensional change at deflasking was reduced.

Kimoto and friends emphasized on the importance of bench cooling in producing the best dimensionally stable acrylic samples (Kimoto et al., 2005). They found similar result but disagreed with the time of delayed flasking. They claimed gradual cooling for 12 hours or more after processing a heat cured acrylic denture is effective in minimizing dimensional inaccuracies of the prosthesis. On the other hand, Anusavice and colleague stated the flask should be removed from water and bench cool for 30 minutes, subsequently immersed in cool tap water for 15 minutes (Anusavice, Phillips, et al., 2013). Furthermore, denture should be stored in water until it is placed in oral cavity to minimize dimensional changes.

2.6 Dimensional stability and accuracy of denture base

In order to fabricate a fitting, retentive and comfortable denture, good dimension stability is important to provide a good adaptation and palatal seal. However, dimensional changes during processing is inevitable, mainly due to polymerization and thermal shrinkage. Other factors influencing dimensional accuracies including powder/liquid ratio, residual ridge height, denture thickness, presence of artificial teeth, separating

medium and the finishing of the processed denture. In short, a good physical property of resin with proper handling during fabrication is the key to produce a dimensionally stable denture.

2.6.1 Factors influencing dimensional stability and accuracies of denture base

2.6.1.1 Investing material

Many studies have discussed the relationship between investing material and tooth movement that occur during processing. In order to overcome this, several authors have proposed the use of a silicone layer cap rather than a gypsum cap during flasking (Marcroft et al., 1961; Reisbick, 1971; Zani & Vieira, 1979). Marcroft named it as layered silicone rubber mold technique which stated that occlusal accuracy obtained with this technique was markedly superior to the usual gypsum technique (Marcroft et al., 1961). However, all other studies claimed there were no significant difference in vertical tooth movement between these two materials (Shibayama et al., 2009; Sotto Maior et al., 2012; Tucker & Freeman, 1971).

Besides silicone cap layer, different methods were recommended by other authors to improve the accuracy of denture. For instance, stone occlusal matrix (Perlowski, 1953; Zakhari, 1976), accurate mesio-distal contacts of artificial tooth (Peyton, 1950) and reduction of the tilt of the investment cast (Lam, 1965).

2.6.1.2 Packing technique

Grunewald and Lam mentioned excess acrylic resin in the mould at the time of final closure or too rapid closure of the flask often cause an increase in vertical dimension (Grunewald et al., 1952; Lam, 1965). Therefore, the flask should be closed under slow, constant pressure (80psi) to allow material to flow into the fine detail and the excess out of the mould (T. Johnson & Wood, 2012).

2.6.1.3 Processing shrinkage and polymerization cycle

As described in 2.2.1 and 2.5.1, PMMA undergoes unavoidable dimensional changes during processing, especially polymerization shrinkage and thermal shrinkage. Mixing PMMA and MMA causes volumetric polymerization shrinkage which ranges between 5-9%, leading to linear shrinkage around 1-2 % (Anusavice, Phillips, et al., 2013; Van Noort & Barbour, 2014).

Literature as discussed in 2.4.1.1 suggested long heat curing cycle at 74ºC for 8 hours and 100ºC for another one hour is optimal for polymerization and produced lesser residual monomer. On the other hand, Mc Cartney mentioned short cycle at 74ºC for 1 1/2 hour and 100ºC for 30 minutes induced more processing shrinkage. There was 25% increase in the posterior palatal region and 50% increase in causing malocclusion when comparing to the longer curing cycle (McCartney, 1984). This was disagreed by Pickett who stated there was no important difference found in terms of fitting between short and long curing cycle (Pickett & Appleby, 1970). However, due to continuous development of material, new short cycle which only required processing 20 minutes in 100ºC was introduced.

2.6.1.4 Cooling methods

After polymerization, cured resin is left to cool down to room temperature with different methods. At this stage, big difference in coefficients of thermal expansion (CTE) between acrylic resin and gypsum matrix produces internal stresses within the processed denture, resulting in thermal shrinkage (Chen et al., 1988; Komiyama & Kawara, 1998). The magnitude of thermal shrinkage closely related to difference between resin glass transition temperature (Tg) and cooling environment. When acrylic resin temperature is above Tg, it is still soft hence will flow into gypsum cast. Subsequently, when cooling proceeds and resins started to harden below Tg, denture base material is forced to comply with the shape of the mold (R Huggett et al., 1990). At this stage, besides the variation in CTE, thermal contraction of acrylic resin is restricted therefore creating more internal

stress within the base. Combination of stresses released during deflasking may later cause dimensional changes or even warpage of the denture (J. F. McCabe & Walls, 2013).

Therefore, as discussed above, many studies emphasized on the importance of bench cooling or gradual cooling in water bath before deflasking to minimize the dimensional changes of heat cured denture base acrylic (Kimoto et al., 2005). Moreover, studies claimed rapid cooling is unacceptable as it showed increase discrepancy in posterior palatal area as well as changes in intermolar distance which can affects the fitting of denture (Chen et al., 1988; Yeung et al., 1995).

2.6.1.5 Finishing

Heat produced by grinding and polishing could soften the resin and produce sufficient stresses leading to warpage of denture. It was found that grinding with carbide burs produced less heat than arbor bands. Thus it should be acknowledged by the dentist and technician that overheating even a small surface may causes dimensional changes resulting in distortion of the denture (Jackson et al., 1989; Lorton & Phillips, 1979).

2.6.1.6 Water sorption

As discussed in 2.2.3, water sorption is one of the characteristics in polymethyl methacrylate. Water molecules ingress into the spaces between polymeric chain causing expansion and small dimensional change (Anusavice, Phillips, et al., 2013). Furthermore, the plasticizing effects facilitate the relaxation of internal stresses build up in the polymeric chains during processing of acrylic resin, especially heat cured. The stress relaxation could possibly contribute to change in shape of the denture (Lamb et al., 2005; Ristic & Carr, 1987).

There are few factors affecting the rate or amount of water sorption. Takahashi and friends mentioned heat cured acrylic resins take a longer time than cold cured acrylic

resins for water sorption to reach saturation due to their lower diffusion coefficient of water (Takahashi et al., 1998). Hence, cold cured resin generally demonstrated slightly greater expansion than heat cured resin after processing during service (Mowery et al., 1958). Thinner denture base specimens take shorter time than thicker specimens to reach water saturation (Sadamori et al., 1997). Changes in temperature influence the rate of water sorption for denture polymers without changing the equilibrium sorption value (Braden, 1964).

Although many studies shown that significant dimensional changes especially expansion of acrylic resins were recognized before and after water immersion (Huggett et al., 1992; Nogueira et al., 1999). Majority of the authors claimed processing shrinkage of denture base acrylic resin could be partly compensated by water sorption (Brauer, 1966; Mowery et al., 1958; Sadamori et al., 1997; Sykora & Sutow, 1993; Woelfel et al., 1961; Wong et al., 1999).

2.6.1.7 Base thickness

Sadamori and colleague reported linear dimensional changes after deflasking were higher in thicker acrylic resin dentures and they take longer to become dimensionally stable (Sadamori et al., 1997). On top of this Jarmani and friends confirmed results of Chen et al although the figures were not as high. These studies showed that tooth movements occurring across the arch are greater in the thick denture bases than in the thinner denture bases. This is because of the heat evolved during the polymerization reaction which would cause the thicker specimen to reach higher temperatures, resulting in greater degree of polymerization (Chen et al., 1988; Jamani & Abuzar, 1998). It is recommended base thickness around 1.5 to 2 mm to avoid this problem (Bonsor & Pearson, 2012).

2.7 Determination of dimensional accuracy of denture base

Many methods have been used to study the dimensional accuracies of denture base materials, ranging from measuring between two reference points on denture base with optical comparator, measuring microscope (Anderson et al., 1988; Huggett et al., 1992; Keenan et al., 2003; Nogueira et al., 1999; Salim et al., 1992), post dam discrepancies (Lamb et al., 2005), vertical dimension or incisor pin movement (Garfunkel, 1983; Strohaver, 1989), quantifying space between denture and master cast with the weight of silicone material (Ganzarolli et al., 2002; McLaughlin et al., 2017) and lately by superimposing scanned data using specified software (Cole et al., 2019; Goodacre et al., 2016; Hwang et al., 2019).

Although manual measuring methods are easy to use, inexpensive and readily accessible, they are time consuming and subject to operator error (Brosky et al., 2002; Dastane et al., 1996). Furthermore, these methods only measure linear changes between two points whereas dimensional changes occurred three dimensionally during processing. Therefore it is more clinical relevant to relate the denture adaptation by superimposing STL files using engineering software (Artopoulos et al., 2013; Goodacre et al., 2016).

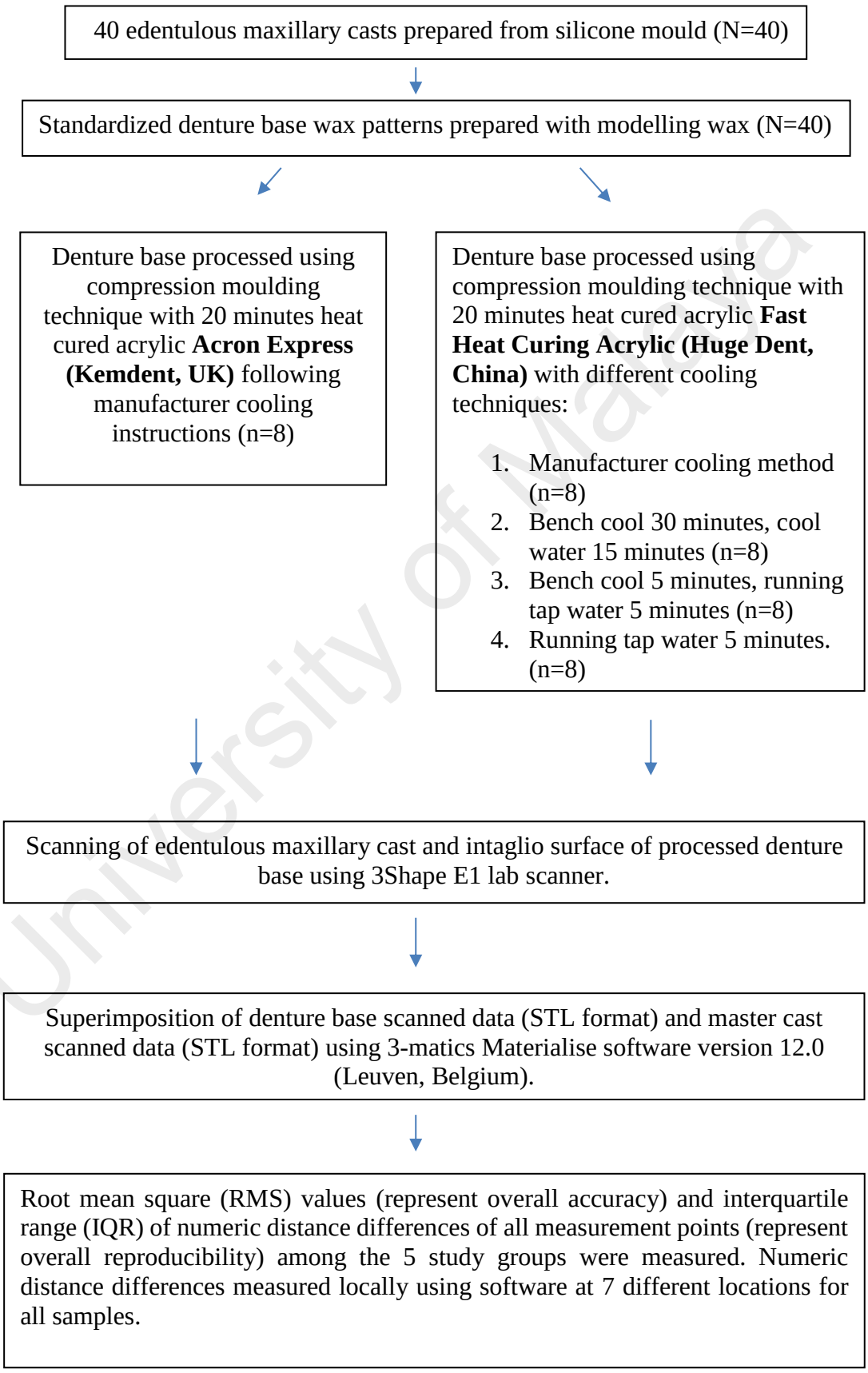
Materialise's 3-matic is a software which combines CAD tools with pre-processing capabilities. It may be used to import anatomical data and other 3D objects in many formats such as STL, CATIA, IGES, STEP and others. 3-matic is used for many applications of "Engineering on Anatomy" to do thorough 3D measurements and analyses, design an implant or surgical guide, or prepare the mesh for finite element modelling (Materialise).

Standard tessellation language (STL) files are most commonly used for surface matching in determining three dimensional changes or fitting of different denture base materials (Goodacre et al., 2016; Hwang et al., 2019). STL file was introduced by 3D

system in 1987, also known as standard tessellation language or Stereolithography file format (Kai et al., 1997). It describes a raw unstructured triangulated surface by the unit normal and vertices of the triangles using a three dimensional cartesian coordinate system (Iancu et al., 2010).

CHAPTER 3: METHODOLOGY

3.1 An overview of the workflow of this study



3.2 Specimen Preparation

3.2.1 Polymethyl methacrylate (PMMA)

Two commercially available PMMA based material namely Acron Express (Figure 3.1) and Fast Heat Curing (Figure 3.2) were used. The product name, code, batch number, manufacturer details of 20 minutes heat cured acrylic denture base materials used in this study are listed in (Table 3.1).

Table 3.1: Manufacturer details, production information of materials used.

20 minutes heat cured acrylic	
Acron Express	**Fast Heat Curing Acrylic**
Powder: Acron Express Pink A199v Associate Dental Products Ltd Kemdent Works, UK Lot: 210605 Expiry date: 12/2020	***Powder:*** Fast Heat Curing Acrylic 2ST Huge Dental Material Co. Ltd Shanghai, China Lot: 1809141101 Expiry date: 10/2021
Liquid: Acron Universal Liquid Associate Dental Products Ltd Kemdent Works, UK Lot: 24512 Expiry date: 09/2019	***Liquid:*** Fast Heat Curing Liquid Huge Dental Material Co. Ltd Shanghai, China Lot: 1808271049 Expiry date: 09/2020

Figure 3.1: Acron Express (Kemdent, UK) powder and liquid.

Figure 3.2: Fast Heat Curing (Huge Dent, China) powder and liquid.

3.3 Preparation of samples

A silicone mould (Wirosil, Bego USA) of an edentulous maxillary arch cast with no severe undercuts was prepared (Figure 3.3).

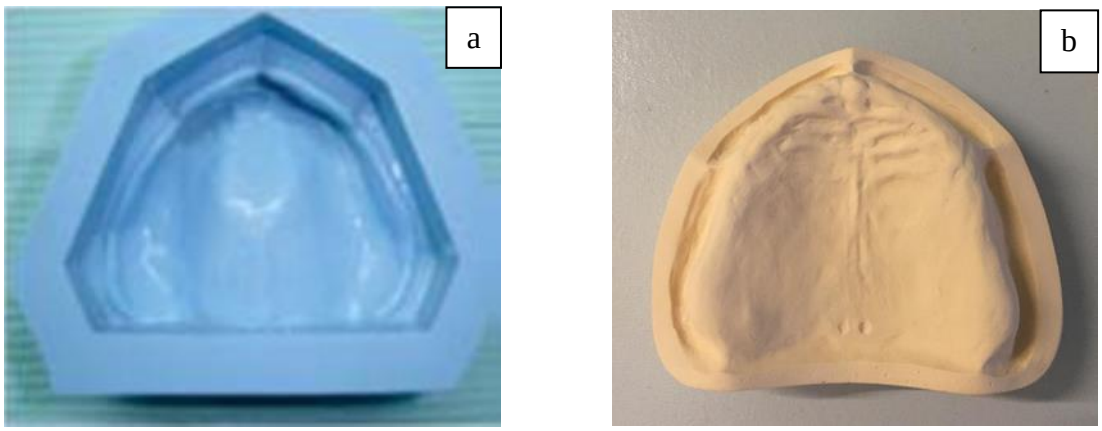


Figure 3.3: (a) Silicone mold for duplication of edentulous maxillary arch cast. (b) Maxillary arch stone cast.

40 standardise casts of edentulous maxillary arches were poured from the silicone mould with Type IV stone (Elite Rock, Zhermack Italy). Powder ratio of 100-gram stone powder to 20 millimetre distilled water was mixed with vacuum mixer (Mulivac® Compact, Degudent Germany) as shown in Figure 3.4 for 30 seconds at 240 rpm.

Figure 3.4: Vacuum mixer (Mulivac® Compact, Degudent Germany) for mixing Type IV stone.

Each cast was trimmed and left dry for 24 hours before scanning with laboratory scanner (E1 3shape, Denmark) which is ISO 12836 certified with accuracy of 10 μm. Casts of maxillary edentulous arch were kept dry in box (Figure 3.5).

Figure 3.5: Casts of maxillary edentulous arch kept dry in box.

A master wax pattern of maxillary denture base with approximately 2.0 millimetres thickness throughout was prepared. In order to standardize the thickness of all samples, a silicone matrix (Exaflex Putty, GC USA) was prepared, three holes were used to create in-gate and vent space in the silicone matrix (Figure 3.6). The matrix was placed on each maxillary edentulous arch cast, melted modelling wax was poured through the holes to replicate the thickness of the master wax pattern.

Figure 3.6: Silicone matrix was used to standardize the thickness of each sample.

Each cast (Figure 3.7) was invested with dental plaster (Plaster of Paris) and type 3 dental stone. The flasks were immersed in warm water (54˚C) for 10 minutes. Flask was opened, wax was removed under running warm water and left to cool down to room temperature (25 ˚C). A thin layer of sodium alginate (Cold Mould Seal, Metrodent, UK) was applied and allowed to dry before packing and processing.

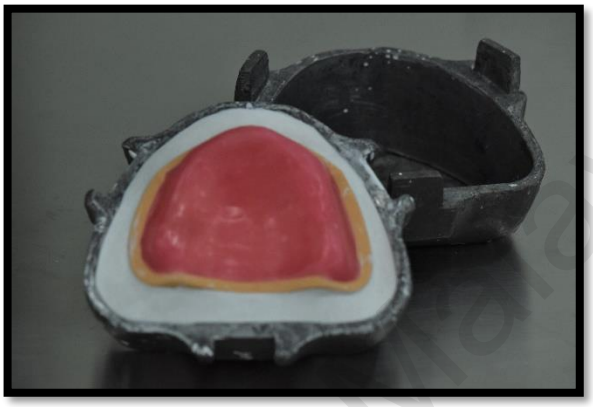


Figure 3.7: Cast with standardized wax pattern invested in denture flask.

The powder to liquid ratio for both Acron Express (Kemdent, UK) and Fast Heat Curing (Huge Dent, China) used in this study is illustrated in (Table 3.2).

Table 3.2: Powder to liquid ratio for both materials

Material	Powder (g)	Liquid (ml)
A. Acron Express (Kemdent, UK)	21	10
B. Fast Heat Curing (Huge Dent, China)	24	10

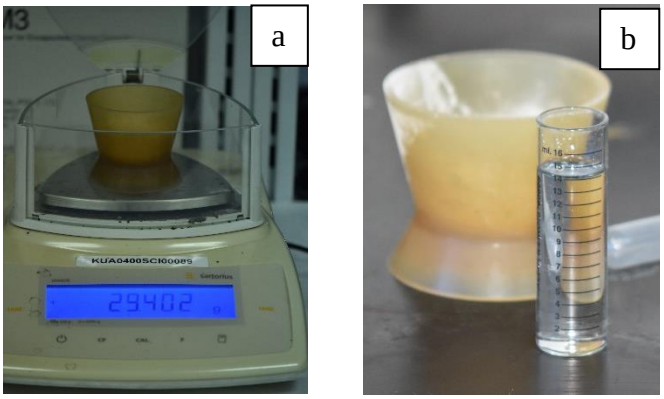


Figure 3.8: (a) Heat cure acrylic powder measured using laboratory electronic scale (Sartorius, Germany) (b) Liquid measured using measuring cylinder (GC, USA)

Heat-cured acrylic powder was measured using laboratory scale (Sartorius, Germany) and the liquid was measured using cylinder (GC, USA) as shown in (Figure 3.8). The acrylic dough was then prepared by thoroughly hand mixing polymer powder with monomer liquid following manufacturer's instructions. The mixture was then kept in a closed silicone cup until dough stage was reached. A polythene sheet was placed over the acrylic dough, trial closure of denture flask was performed with bench hydraulic pressure of 1000 psi with pressure slowly increased over a period of one minute. After discarding the separating sheet and excess flash, second trial closure was repeated with the pressure held for ten minutes. When no further flash was evident, the mould was then closed without separating sheet to a pressure of 1000 psi. After removal from hydraulic bench press, the flask was placed into a dental laboratory spring compressor to maintain continuous pressure on the polymethyl methacrylate (PMMA) during processing.

Water bath was prepared to reach 100˚ C. This was indicated on dental laboratory polymerizer (Acrydig 10 Manfredi, Italy) as shown in (Figure 3.9) which was further verified by laboratory thermometer. The acrylic in packed mould was then polymerized by heating for 20 minutes at 100˚C water bath as controlled by build in thermostat. Digital timer was used to double check the duration along the polymerization process. Samples

were then subject to different cooling methods according to assigned groups as explained in (Table 3.3).

Figure 3.9: Dental laboratory polymerizer (ACRYDIG 10 Manfredi, Italy).

Table 3.3: Specimen groups according to material and different cooling methods.

Groups	Types of materials	Cooling methods
A1	Acron Express (Kemdent, UK)	Follow manufacturer instructions (bench cooling 30 minutes, immerse in room temperature water bath for 20 minutes before deflasking).
F1	Fast Heat Curing (Huge Dent, China)	Follow manufacturer instructions (bench cooling until cool down completely), then deflask.
F2	Fast Heat Curing (Huge Dent, China)	Bench cooling 30 minutes & immerse in room temperature water bath for 15 minutes, then deflask.
F3	Fast Heat Curing (Huge Dent, China)	Bench cooling for 5 minutes, place under running tap water for another 5 minutes, then deflask.
F4	Fast Heat Curing (Huge Dent, China)	Immerse directly into room temperature water bath with running tap water for 5 minutes, then deflask.

Processed denture base was removed from flask gently, excess acrylic flash was removed with acrylic trimming burs at slow speed (20 000 rpm) without polishing. All denture bases were hydrated with distilled water for around 24 hours prior to scanning procedure.

3.4 Scanning of specimens

Denture bases were lightly coated with anti-glare spray (3-D laser scanning anti-glare spray; Helling). The specimens were supported by using single putty index (Exaflex Putty, GC USA) to ensure similar location and angulation during scanning (Figure 3.10). All intaglio surfaces were scanned using 3Shape E1 scanner (3shape A/S, Denmark) and exported as STL files.

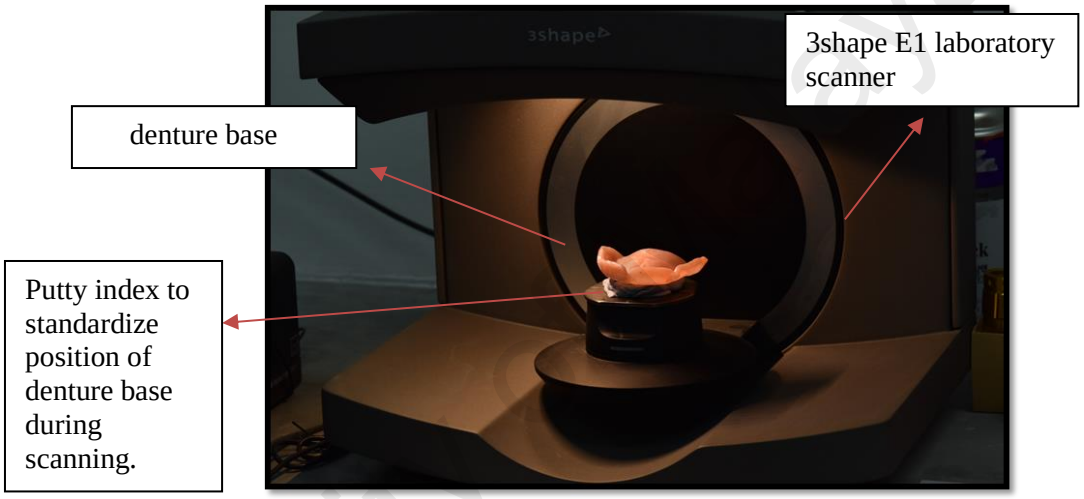


Figure 3.10: Denture base was placed on putty index. Scanning of intaglio surface was done using 3shape E1 laboratory scanner

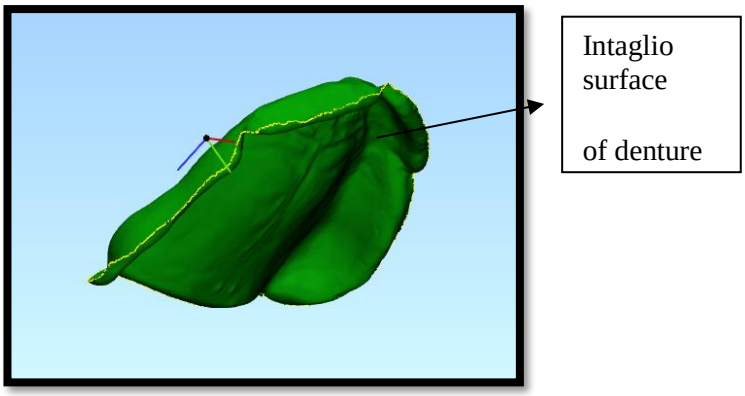


Figure 3.11: STL file of the scanned intaglio surface shown in 3-matics Materialise software version 12.0 (Leuven, Belgium)

The STL file of each denture base's intaglio surface (Figure 3.11) was superimposed with scanned master cast STL file to analyse the adaptation of each specimen. Superimposition was done manually using four anatomical landmarks with N point registration and followed by fine tuning with automated registration or also known as global registration. Besides collecting root mean squared value for each sample, numeric distances were recorded in seven different locations including incisive papillae, crest of anterior and posterior ridge, posterior palatal seal, 6.0 mm from denture border and at the buccal slope (Figure 3.12).

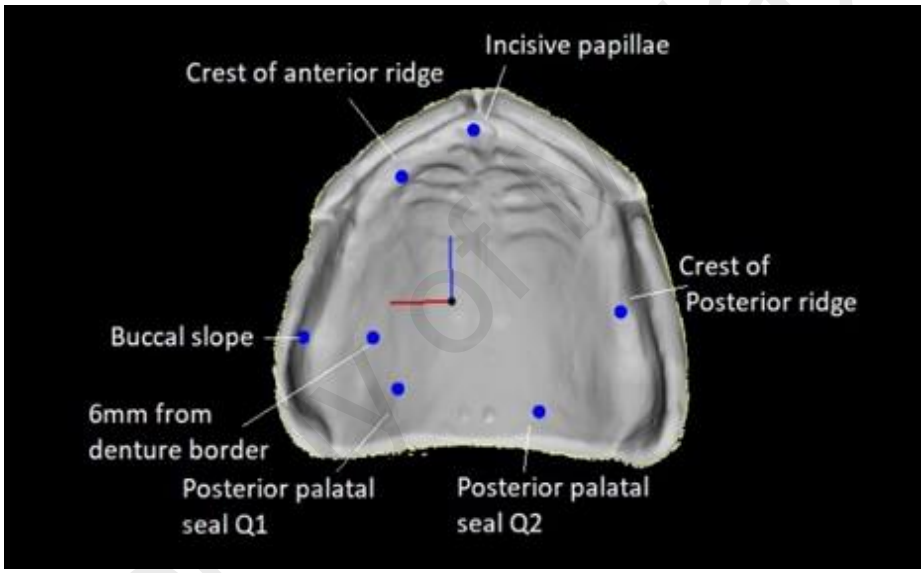


Figure 3.12: Scanned master cast STL file with 7 dots at different locations

3.5 Superimposition of standard tessellation language (STL) files

Irrelevant area was removed using 3-matics software version 12.0 (Leuven, Belgium). The STL file of each denture base's intaglio surface was superimposed with scanned master cast STL file to analyse the adaptation of each specimen. Superimposition was done manually using four anatomical landmarks (labial frenum, buccal frenums and fovea palatini) with N point registrations (point-to-point registration) and followed by fine tuning with automated registration or also known as global registration adopting closest

point algorithm of the software. Color-coded surface deviation maps were visually displayed. Each scanning and superimposition were performed by a single investigator. The ideal denture would show a colour map which was entirely green, giving a measurement of 0, which indicates ideal adaptation of denture base to master cast. Positive deviations (yellow to red colour) showing misfit with gap and negative deviations (cyan to blue colour) showing denture base is impinging into master dental cast.

The means, standard deviations, and interquartile ranges of numeric distance (mm) for all measurement points in each superimposition were extracted from 3-matics software (Figure 3.13). With regards to overall denture base adaptation, lower RMS value which is closer than 0 indicates better adaptation. On the other hand, a narrow interquartile range of numeric distance (mm) represents higher reproducibility of the material or cooling methods to create a well-adapted denture base each time a denture is produced according to allocated specimen groups.

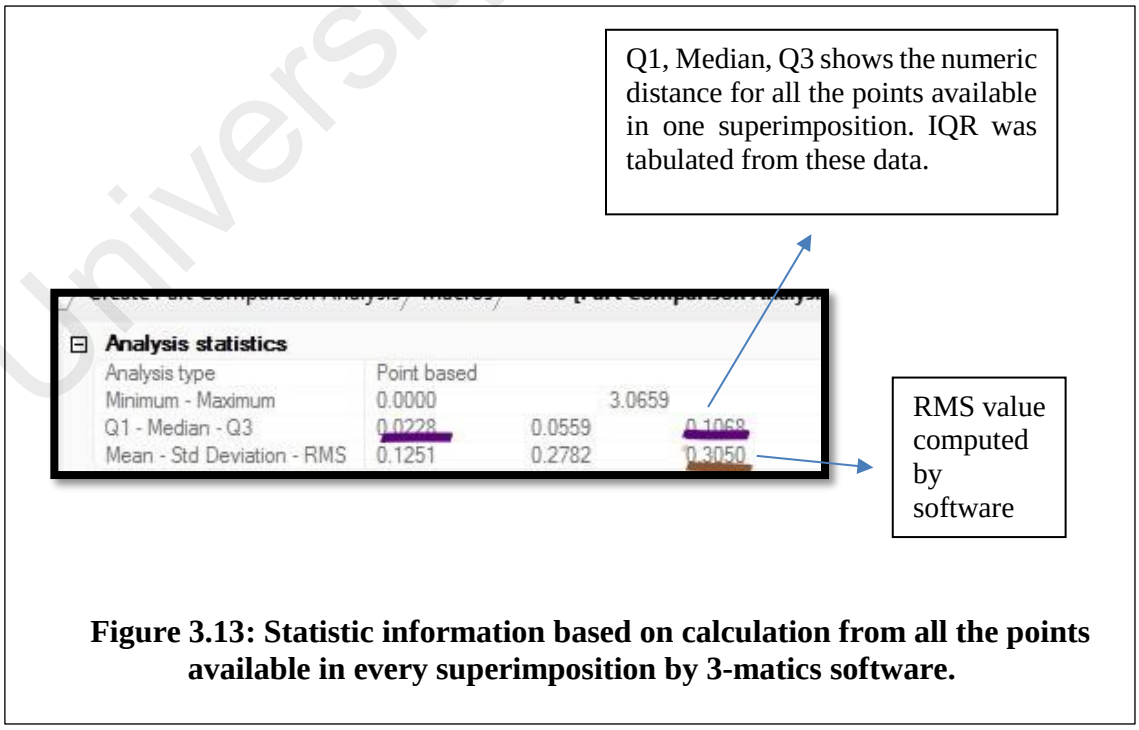


Figure 3.13: Statistic information based on calculation from all the points available in every superimposition by 3-matics software.

Besides that, numeric distances were recorded at seven different locations (incisive papillae, crest of anterior and posterior ridge, posterior palatal seal, 6.0 mm from denture border and at the buccal slope). These locations were standardized by superimposing all the specimens against the same master cast STL file marked with seven fixed points (Figure 3.12).

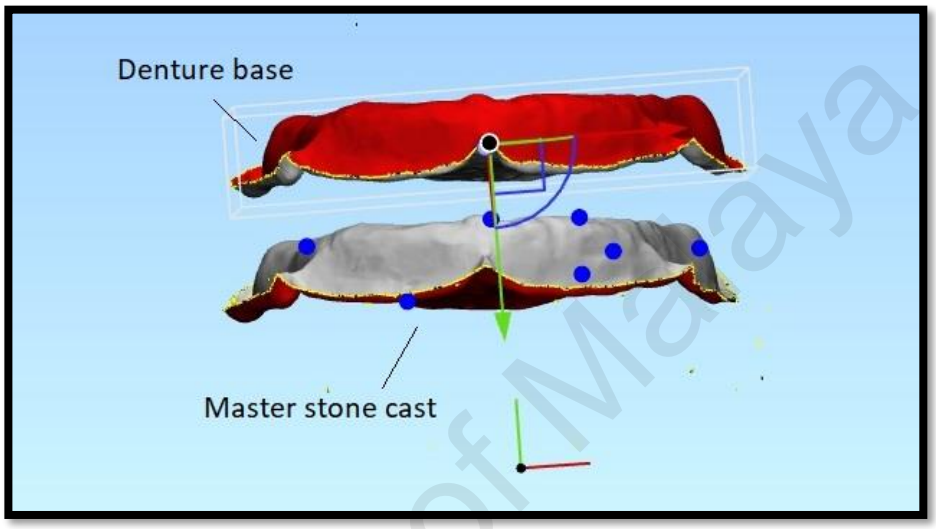


Figure 3.14: Superimposition of denture base STL file on master stone cast STL file.

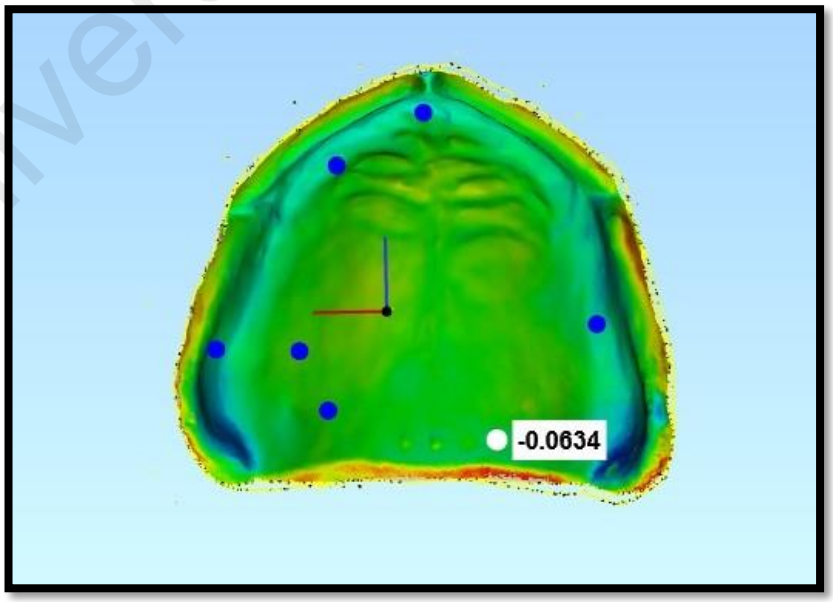


Figure 3.15: Numeric distance (mm) shown by 3-matics software version 12.0 (Leuven, Belgium) by placing cursor at standardized point.

3.6 Statistical analysis

Statistical analysis was performed on all the data collected using SPSS® (SPSS Inc., IBM, USA) and Microsoft Excel © (Microsoft® Corporation, USA) software. Quantitative analysis was performed to check for statistical differences between the mean of root mean square value and interquartile range of numeric distance differences. After checking the data was normally distributed as shown in (Appendix B), a one-way analysis of variance (ANOVA) was used to compared between specimen groups (A1, F1, F2, F3, F4). A significance level of $p<0.05$ was set. Post hoc analysis was carried out if there were significant differences amongst the group from the ANOVA test ($p<0.05$).

For determining numeric distance differences at seven specified locations (Figure 3.15), intraclass correlation coefficient (ICC) was conducted to ensure the reliability of measurements taken by the single investigator, score of 0.846 was reported to ensure high intra-rater reliability. Furthermore, as the data was normally distributed, a two-way analysis of variance (ANOVA) was conducted on the influence of two independent variables namely the specimen groups and different locations on the numeric distance (mm) measured.

To determine the consistency of dental cast duplication from silicone mould, six dental cast were duplicated from same silicone mould. These models were scanned using E1 3Shape laboratory scanner (3shape A/S, Denmark). All scanned images were exported in STL format. The STL file of five dental casts was superimposed against one STL file of the dental cast. RMS value for each superimposition was recorded.

CHAPTER 4: RESULTS

4.1 Root mean square value for each superimposition

Root mean square (RMS) value of Acron Express (A1) and Fast Heat Curing with different cooling methods (F1, F2, F3, F4) are shown in (Figure 4.1) and (Table 4.1). F1 specimen group which was cooled down according to manufacturer's instruction shows the lowest mean RMS values compared to other groups. As comparison, F3 and F4 groups which were cooled down rapidly show higher mean RMS value.

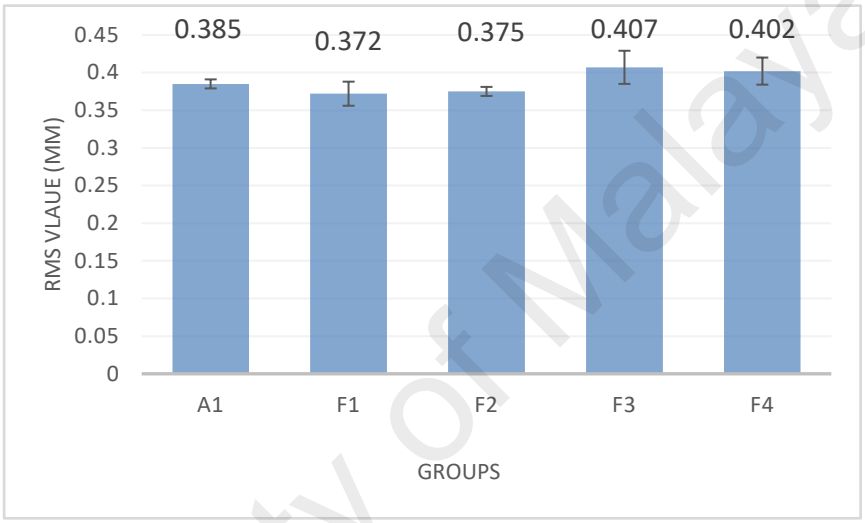


Figure 4.1: Mean RMS value of all specimen groups with 95% confidence interval error bar.

Table 4.1: Mean RMS value of all specimen groups.

Groups	Mean of RMS value (mm)	Standard Deviation (±0.001)
A 1	0.385	0.007
F 1	0.372	0.008
F 2	0.375	0.003
F 3	0.407	0.110
F 4	0.402	0.009

Prior to data analysis, all variables were subjected to normality test and the results revealed all research variables were distributed normally. As shown in (Table 4.2), Levene's test showed that the variance for root mean square value were not equal, $F(4,35)=6.923$, $p< 0.05$.

Table 4.2: Test of homogeneity of variances for mean RMS value.

	Levene Statistic	df1	df2	P value
Mean RMS value	6.923	4	35	.000

(Table 4.3) shows Welch test results for mean RMS value (Welch = 3.775, $p<0.05$) indicated a significant difference between the overall means.

Table 4.3: Welch statistic for mean RMS value.

	Welch Statistic	df	P value
Mean RMS value	3.775	4	0.023

In addition, Tamhane post hoc test was applied to compare means of RMS value among different specimen groups. However, as attached in Appendix C, the results show mean RMS value are not statistically different between A1, F1, F2, F3 and F4 at 95% ($p<0.05$) interval.

4.2 Mean of interquartile range for numeric distance in each superimposition

Mean value of interquartile range based on numeric distance in one superimposition of all specimen groups are shown in (Figure 4.2) and (Table 4.4). F1 specimen group which was cooled down according to manufacturer's instruction shows the lowest IQR as compared to other groups. On the other hand, F3 and F4 groups which were cooled down rapidly show higher range of IQR. F4 with shortest cooling period shows highest score of 0.157 mm.

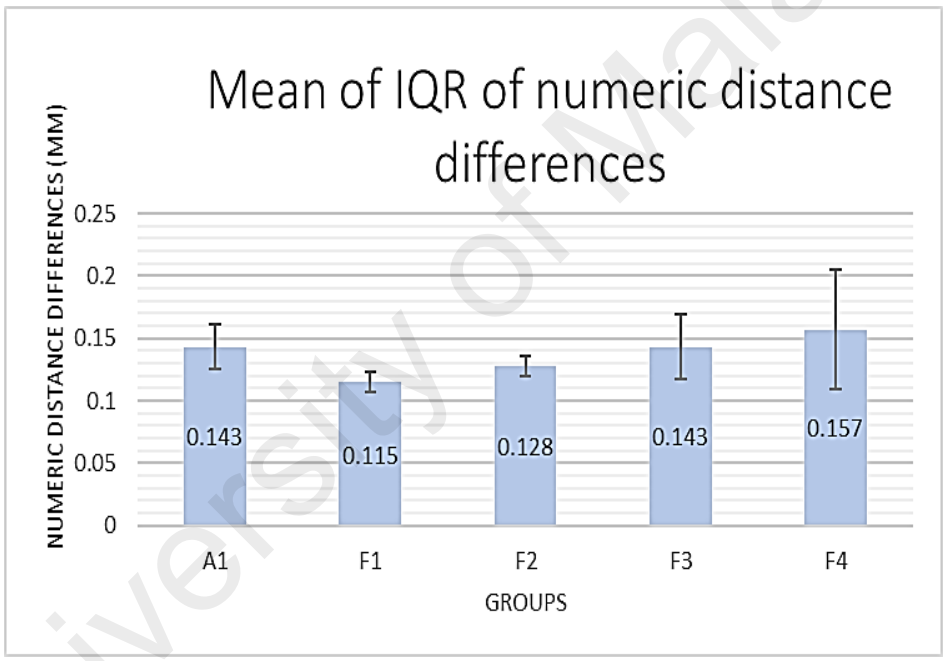


Figure 4.2: Mean of IQR of numeric distance differences (mm) with 95% confidence level error bar.

Table 4.4: Mean IQR of numeric distance (mm) for all specimen groups.

Groups	Mean IQR of numeric distance (mm)	Standard Deviation (±0.001)
A 1	0.143	0.009
F 1	0.115	0.013
F 2	0.128	0.012
F 3	0.143	0.037
F 4	0.157	0.068

Before data analysis, all variables were subjected to normality test and the results revealed all research variables were distributed normally. As shown in (Table 4.5), Levene's test showed that the variance for root mean square value were not equal, $F(4,35)=4.102$, $p< 0.05$.

Table 4.5: Test of homogeneity of variances for mean IQR of numeric distance for all specimen groups.

	Levene Statistic	df1	df2	P value
Mean RMS value	4.102	4	35	.008

Welch test results for mean IQR of numeric distance measured (Welch = 3.030, $p<0.05$) indicated a significant difference between the overall means (Table 4.6).

Table 4.6: Welch statistic for Mean IQR of numeric distance measured among different specimen group.

	Welch Statistic	df	P value
Mean RMS value	3.030	4	0.048

In addition, Tamhane post hoc test was applied to compare means of interquartile range (IQR) of numeric distance measured among different specimen groups. However, as attached in Appendix D, the results show mean IQR value are not statistically different between A1, F1, F2, F3 and F4 at 95% ($p<0.05$) interval.

4.3 Color maps analysis using 3-matics version 12.0 (Leuven, Belgium)

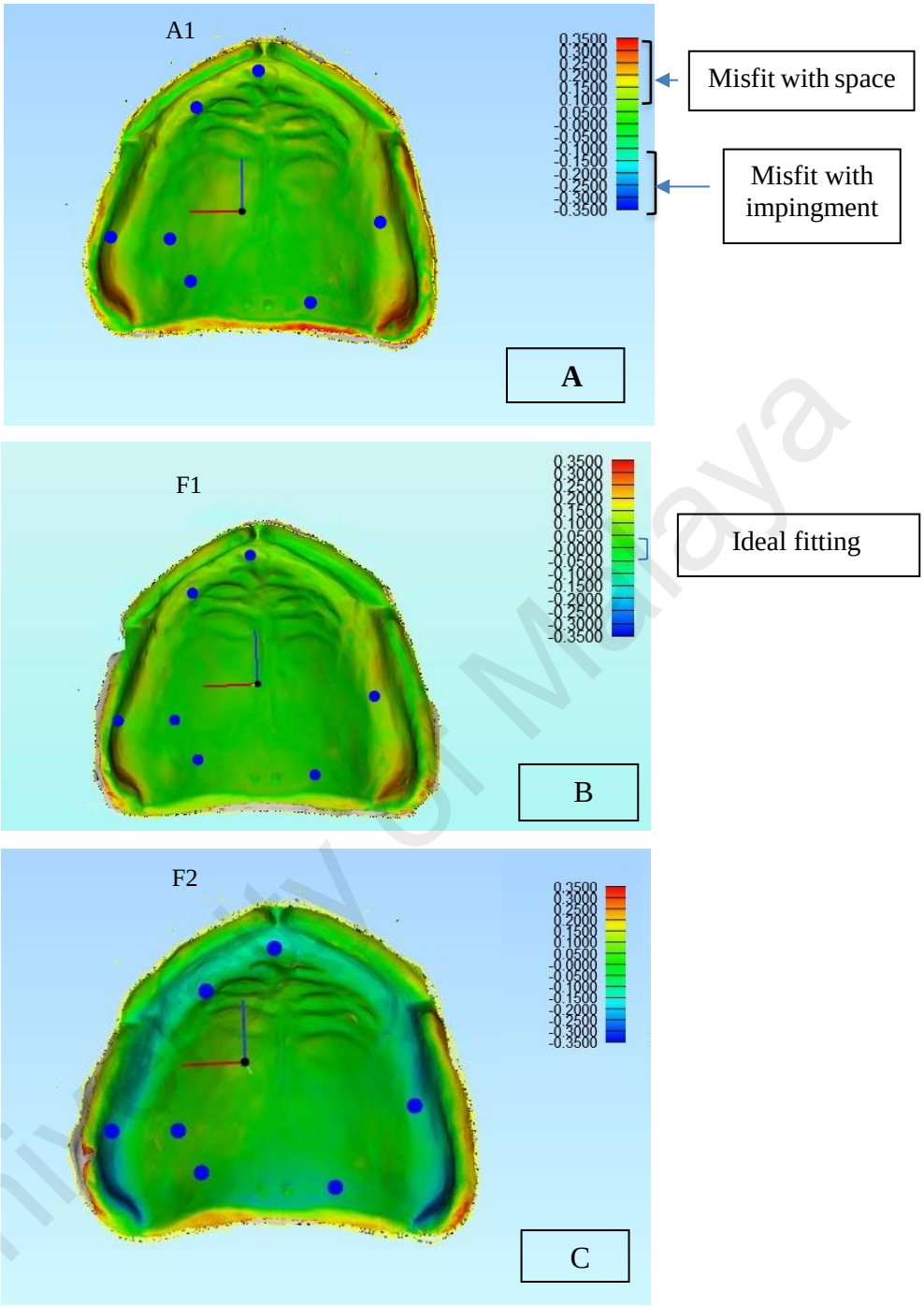


Figure 4.3: Color map of denture base adaptation of (A) Acron Express A1 group when cool down according to manufacturer's instructions. (B) Fast Heat Curing Acrylic (Huge Dent, China) F1 group when cool down according to manufacturer's instructions. (C) Fast Heat Curing Acrylic (Huge Dent, China) F2 group with 30 minutes bench cooling.

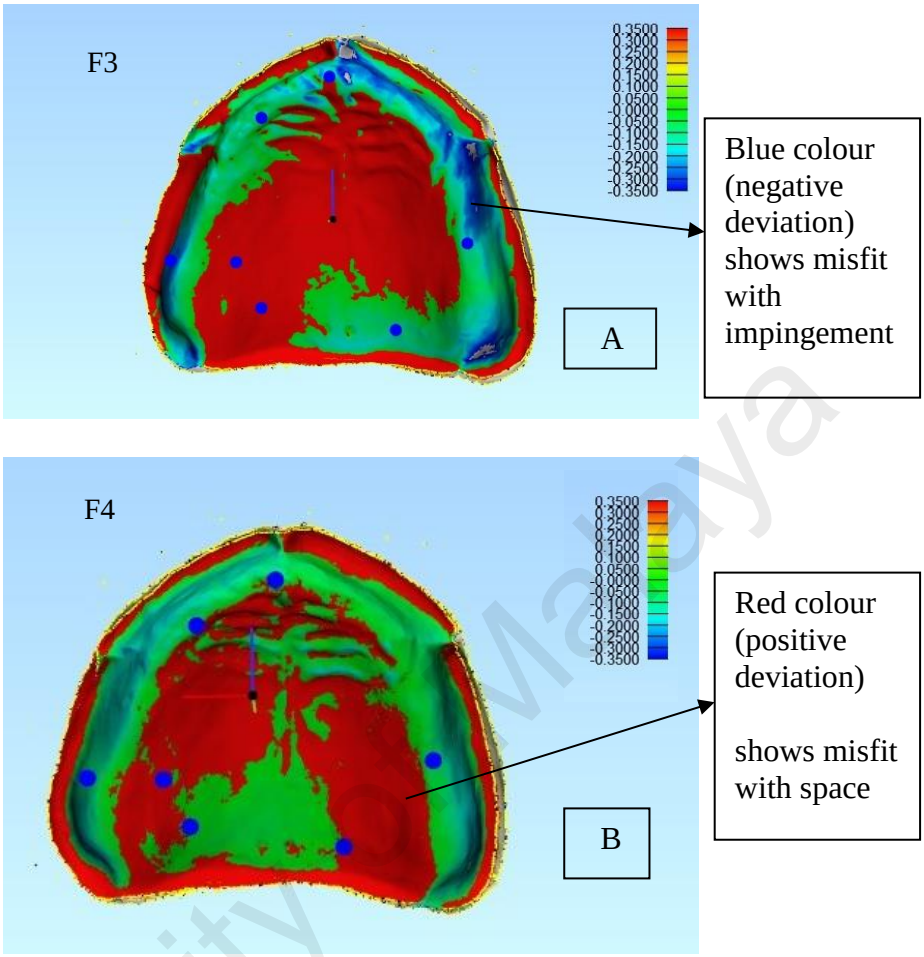


Figure 4.4: Color map of denture base adaptation of (A) Fast Heat Curing Acrylic (Huge Dent, China) F3 group with bench cooling for 5 minutes then place under running water for 5 minutes. (B) Fast Heat Curing Acrylic (Huge Dent, China) F4 group which was cooled down by placing under running water for 5 minutes.

4.4 Numeric distance measured (mm) of different specimen groups measured at different locations

The effect of different specimen groups and locations on numeric distance (mm) measured were analysed based on two-way ANOVA. Different specimens included 5 levels (A1, F1, F2, F3, F4) and location consisted of seven levels (incisive papillae, crest of the anterior ridge, buccal slope, 6mm from denture border at the palate, posterior palatal seal at quadrant one, posterior palatal seal at quadrant two and crest of posterior ridge). Prior to data analysis, data were subjected to normality test and the results showed normal distribution. Significance level was set at p=0.05. As there is equal sample size for each group, homogenous of variance is assumed.

The main effect for different specimen groups yielded an F ratio of $F(4, 245)=1.75$, p=0.139 indicating no significant difference at 0.05 significance level between A1(M=0.035,SD=0.087), F1(M=0.046,SD=0.093), F2(M=0.024,SD=0.112), F3(M=0.028,SD=0.102), F4(M=0.238,SD= 0.112). The main effect of different locations yielded an F ratio of $F(6, 245)= 0.416$, p=0.868 indicating the effect of location was not significant, incisive papillae (M=0.204,SD=0.183), crest of the anterior ridge (M=0.03,SD=0.087), buccal slope (M=0.043,SD=0.12), 6mm from denture border at the palate (M=0.011,SD=0.075), posterior palatal seal at quadrant one (M=0.026,SD=0.080), posterior palatal seal at quadrant two (M=0.015,SD=0.082) and crest of posterior ridge (M=0.034,SD=0.088). Line graph (Figure 4.5) shows interaction of numeric distance measurement of different specimen groups at different locations. However, the interaction effect was not statistically significant, $F(24,245)=0.648$ with p=0.897 as shown in (Table 4.9).

Table 4.7: Descriptive statistics for numeric distance (mm) of different specimen groups

Specimen Groups	Mean (M)	Standard deviation (SD)
A1	0.035	0.087
F1	0.046	0.093
F2	0.024	0.112
F3	0.028	0.102
F4	0.238	0.112

Table 4.8: Descriptive statistics for numeric distance (mm) at different locations.

Locations	Mean (M)	Standard Deviation (SD)
Incisive papillae	0.204	0.183
Crest of anterior ridge	0.030	0.087
Buccal slope	0.043	0.120
6mm from denture border at palate	0.011	0.075
Posterior palatal seal at quadrant one	0.026	0.088
Posterior palatal seal at quadrant two	0.015	0.082
Crest of posterior ridge	0.034	0.088

Table 4.9: Summary of ANOVA (MS) for effect of different specimen groups and locations on numeric distance (mm)

Source	SS	df	MS	F	P value	Partial Eta Squared
Specimen groups	0.084	4	0.021	1.753	0.139	0.028
Locations	0.030	6	0.005	0.416	0.868	0.10
Specimen groups*Locations	0.186	24	0.008	0.648	0.897	0.060

SS=sum of squares, MS= mean square

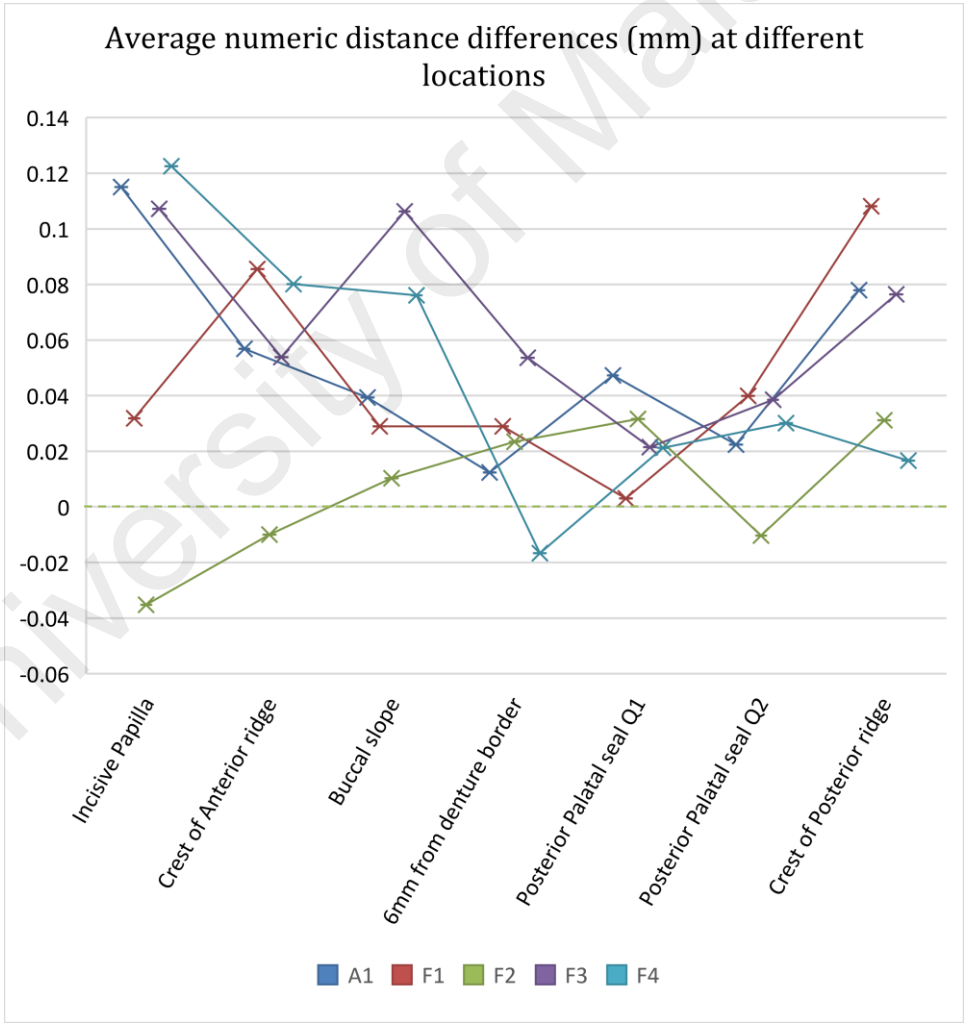


Figure 4.5 Numeric distance differences (mm) for each specimen group at different locations.

4.5 Comparison of root mean square (RMS) value (mm) between superimposition of duplicated master dental casts.

One sample T test showed there was no statistically significant difference between means (p>0.05) of duplicated casts with the control cast. Test value was set at 0 as this indicates ideal matching with no differences between two scanned files. No significant differences amongst the group from the ANOVA test (p<0.05) as shown in (Table 4.10). Therefore, null hypothesis is accepted, there is no difference between the duplicated casts and the master cast.

Table 4.10: One sample T test RMS value (mm) of six duplicated cast.

Variable	Mean (SD)	t value	p value	95% CI of difference	
				Lower	Upper
RMS	0.324 (0.655)	1.213	0.279	-0.363	1.012

Test value = 0

CHAPTER 5: DISCUSSION

A recent study reported 77.1 % of Malaysian older adults have less than 20 teeth, and about 18.3 % are edentulous (Rosli et al., 2018). This finding is associated with reduced oral health related quality of life among Malaysian geriatric population which reflects high treatment need. In other words, this implies more than half of these elderly will need removable prosthesis. Although there are options such as cobalt chrome denture and implant retained denture, majority of the patients opt for acrylic prosthesis due to cost and lack of access to care (Cunha et al., 2013; Vecchia et al., 2014).

There have been continuous improvisations of clinical procedures, dental materials as well as laboratory processing techniques to fulfil the high demand of acrylic prosthesis (Cunha et al., 2013; Ilbay et al., 1994). A systematic review by Paulino and friends concluded that despite reduction of clinical steps such as functional impression, facebow record and clinical remount, there is no difference in masticatory variables, quality of dentures and patient satisfaction. Although more high-quality studies are needed to finalize the statement, the selected studies show the importance of time consumption and cost effectiveness in providing prostheses to patients (Paulino et al., 2015).

Apart from clinical steps, time taken for laboratory procedures is closely related to the overall duration needed to deliver a prosthesis. Conventional heat curing cycle suggested processing denture base in 74˚C water bath for 8 hours before increasing the temperature to 100 ˚C for another one hour (Jagger, 1978). This step contributes to most of the time taken during denture processing. On top of that, a longer cooling period is suggested to minimise dimensional inaccuracies of the prosthesis. However, the duration is wide ranging from 30 minutes bench cooling followed by immersing in cool tap water for 15 minutes (Anusavice, Phillips, et al., 2013) to bench cooling more than 12 hours (Kimoto et al., 2005). In this study, the manufacturer's instruction for Fast Heat Curing acrylic was

to bench cool until cool down completely which is similar to what is suggested by Kimoto et al. (2005). On the other hand, manufacturer's instruction for Acron Express was similar to the suggestion by Anusavice and colleagues (2013).

An affordable and short processing method which can reduce denture delivery time is important especially for target geriatric population who have contraindicating pathologies, chronic diseases, or significant social and economic disadvantages (Ceruti et al., 2017). A shorter processing and cooling time can then maximise clinical steps accomplished per day. This reduces the need to travel for patients with decreased mobility and reduced freedom of movement, or for those living in rural areas where public transport options may be costly and limited. Several studies reported 20 minutes heat cured acrylic is comparable with conventional heat cured acrylic (Firtell et al., 1981; Negreiros et al., 2009; Polychronakis et al., 2003). However, there is a lack of studies which investigate Fast Heat Curing Acrylic (Huge Dental Material, China) that is widely used in Malaysia's commercial dental laboratories.

The functionality of a complete denture is closely related to the adaptation of its base to the supporting areas. Apart from anatomical factors, denture stability and retention can be improved by better adaptation of denture base. Patient's satisfaction is improved consequently (Darvell & Clark, 2000; Ganzarolli et al., 2002). Therefore, the first objective of this study was to investigate the difference in dimensional stability of Acron Express (Kemdent, UK) and Fast Heat Cure (Huge Dent, China) in relation to denture base adaptation when cooling according to manufacturer instructions.

In order to focus on effect of cooling methods, other factors which may affect dimensional stability and adaptation of denture base were controlled consistently in this study. For example, denture base thickness, palatal form, period of hydration prior to scanning, calibrated laboratory scanner and standardized superimposition protocol.

Furthermore, denture base was kept hydrated in distilled water for not longer than 24 hours prior to scanning as explained by Goodacre et al. (2016) and Norvell et al. (2018) to simulate the fitting of hydrated denture base when patient is wearing the denture.

Metal spheres incorporated in master casts are used as a guides for superimposition (Goodacre et al., 2018). However, more recent studies have suggested that anatomic non-invasive landmarks are reliable markers for the superimposition of corresponding digital surface scan without incorporation of markers on master cast (Norvell et al., 2018). Therefore, anatomical landmarks in maxillary edentulous arch were selected as markers during STL files superimposition in this study.

While most studies advocate scanning each master cast before processing corresponding denture case (Artopoulos et al., 2013; Hwang et al., 2019), only one digitized master cast file was used in this study for every specimen. The rationale was to standardize measurements at specified locations on each superimposition as described in (Figure 3.12). Six master models were duplicated from silicone mould, scanned and superimposed to compare the discrepancy between these models. (Table 4.10) shows the differences between the scanned models were not statistically significant. Hence, we can presume using one single digitized master cast is equivalent to scanning each corresponding cast which will involves more time and cost. This suggestion may be incorporated in future studies with similar research protocols.

Based on mean of root mean square (RMS) value, overall accuracy of F1 (Fast Heat Curing Acrylic, Huge Dent China) is comparable to A1 (Acron Express, Kemdent UK) when cooled down according to manufacturer instructions since the difference was not statistically significant. The IQR of overall numeric distance differences is associated with the reproducibility of the selected material or processing method (Goodacre et al., 2016, 2018; Hwang et al., 2019). In this study, accuracy and reproducibility of both A1

and F1 groups are comparable between two groups. These findings imply F1 is a viable option for fast cooling heat cured acrylic in terms of accuracy and reproducibility when cooled down according to manufacturer's instructions.

Second objective aimed to investigate the effect of different cooling methods on fast heat curing acrylic. Fast Heat Cure (Huge Dent, China) when allowed to bench cool (F1, F2) showed better accuracy and reproducibility compared to rapid cooling groups (F3, F4). These findings were similar to other studies which show less dimensional changes in bench cooling group (Chen et al., 1988; Ganzarolli et al., 2002; Kimoto et al., 2005). During heat polymerization, difference in thermal contraction between stone mould and acrylic resin has led to production of internal stress within processed denture (J. McCabe & Wilson, 1980). This residual stress is released upon deflasking. Hence, higher shrinkage of fast cooling denture was found compared to slow cooling group as more elastic strain was released during removal from stone mould (Chen et al., 1988; Komiyama & Kawara, 1998).

This effect of such shrinkage can be visualised on colour maps as shown in (Figure 4.3 and Figure 4.4). Ideal adaptation is shown as homogenous green area (such as in F1and F2) whereby in these groups, denture base made of Fast Heat Curing (Huge Dent, China) were subjected to bench cooling. Positive deviation which indicates space between two surfaces will be shown in gradient colour from yellow to red (for example F3 and F4 which were subjected to rapid cooling). Presence of spaces especially at posterior palatal seal area as shown in (Figure 4.4) indicates there may be warpage of denture upon deflasking in rapid cooling groups (F3-F4). However, as mucosa is compressible during function, the effect this gap which is less than 1 mm is not known clinically.

While the RMS value and colour map indicate F3 and F4 were less accurate compared to bench cooling groups (A1, F1 and F2) the differences were not statistically significant.

Thus, bench cooling still the cooling method of choice when using Fast Heat Cure (Huge Dent, China). However, if shorter delivery time is required; for instance, during community service at rural areas, surgical plate for oral cancer patients and orthodontic retainer, 5- or 10-minutes rapid cooling methods (F3, F4) are viable options to process a clinically acceptable complete dentures in terms of denture base adaptation.

The adaptation of denture base (A1, F1, F2, F3, F4) at predetermined locations was assessed as the third objective in this study. Unlike first and second objective, the numeric distance between the denture base and master cast was measured locally at seven fixed points. F2 bench cooling group showed the best accuracy when measured at crest of anterior ridge, buccal slope and posterior palatal seal. On the other hand, F1 group was superior in terms of reproducibility at incisive papilla, crest of anterior ridge and 6 mm from denture border. Although these findings were similar to the overall discrepancy shown by RMS values, the differences were not statistically significant. Furthermore, based on (Figure 4.5), the readings were least scattered in posterior palatal seal which is important in providing a retentive complete denture. Within the limitations of this study, these show that all specimen groups with different material and cooling methods were able to produce comparable denture base adaptation.

5.1 Limitations

One of the limitations of this *in vitro* study was that the denture base adaptation was compared against a standard edentulous master cast. The master cast does not replicate the dynamic characteristic of oral mucosa during function. Contrary to a similar study by Jang et al (2019) regarding accuracy of three units fixed prosthesis fabricated on 3D printer cast, unlike fixed prosthesis, adaptation of removable prosthesis is highly influenced by compressibility of mucosa during mastication (Cook, 1991). Furthermore,

master cast with limited undercut in this study does not represent anatomical varieties in actual patients.

On the other hand, the software first performed point-based registration using fixed anatomical landmark followed by overall matching using closest corresponding points between two surfaces. Due to the complicated algorithm in the process of automated superimposition, true individual displacement may not be replicated accurately. However, to date this remains the most updated research protocol for similar study. In order to improve this limitation, haptic technology should be incorporated into the alignment software to relate it to actual tactile sensation occur during denture base adaptation (Norvell et al., 2018).

Another limitation of the study is that the scanning was performed within 24 hours after processing the denture base. Thus, aging of the material upon clinical usage was not taken into consideration in our study. We have yet to probe into longevity of the denture base. Long term cost effectiveness of the denture base was also not investigated compared to other processing techniques. Hence, thermocycling process should be incorporated in future studies. Nevertheless, more clinical and patient related outcome research shall be conducted to evaluate clinical outcome.

CHAPTER 6: CONCLUSION

The following conclusions were made:

a. When cool down according to manufacturer's instructions, overall accuracy and reproducibility of Fast Heat Curing Acrylic (Huge Dent, China) was comparable to ISO 20795-1:2013 certified Acron Express (Kemdent, UK).
b. Denture base adaptation of Fast Heat Curing Acrylic (Huge Dent, China) bench cooling groups (F1, F2) exhibited better accuracy and reproducibility as compared to rapid cooling groups (F3, F4). However, the differences were not statistically significant. Therefore, within the limitation of this study, all groups produce comparable denture base in terms of accuracy and reproducibility.
c. There is no significant differences of accuracy and reproducibility between Fast Heat Curing Acrylic (Huge Dent, China) bench cooling groups (F1, F2) and rapid cooling groups (F3, F4) at different specified locations.

CHAPTER 7: RECOMMENDATIONS

The recommendations for future research are as follow:

1. In-depth exploration of chemical structure, functional groups and bonds in rapid heat cured acrylic, Fast Heat Curing (Huge Dent, China). Fourier-transform infrared spectroscopy (FTIR) should be conducted to investigate the composition of this material which allowed shorter polymerization with rapid cooling.
2. More research is warranted to study the properties of rapid heat cured acrylic as listed in ISO 20795-1:2013. For example, mechanical properties, amount of residual monomer and water sorption.
3. Study on the effect of thermocycling on rapid heat cured acrylic resin when subjected to different cooling methods is helpful in simulating aging process of this material.
4. Further clinical studies are needed to determine clinical longevity and patient related outcome.

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LIST OF PUBLICATIONS AND PAPERS PRESENTED

1. "A Narrative Review of Different Types and Processing Methods of Acrylic Denture Base Material" published in Ann Dent UM. 2018, 25(2):58-67.