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**Dimensional precision and volumetric shrinkage of PMMA denture  
bases polymerized with different methods**

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**List of abbreviations:**

DB:	Denture base
CC:	Cold-cured
CM:	Compression-molding
CRDP:	Complete removable dental prosthesis
CTE:	Coefficient of thermal expansion
HC:	Heat-cured
IM:	Injection-molding
MC:	Microwave-cured
MMA:	Methylmethacrylate
PMMA:	Polymethylmethacrylate
PPS:	Posterior palatal seal
S.D.:	Standard deviation
Tg:	Glass transition temperature

# 1 Introduction

## 1.1 Retention of complete removable dental prostheses

Complete removable dental prostheses (CRDPs) have to function well and be aesthetically acceptable; that means they should be comfortable, retentive, stable, and displaying a natural looking. Undoubtly, restoring the missing teeth, resorbed bone, loss in vertical dimension, and restoring the speech are fundamentals that need to be fulfilled in every CRDP treatment [24, 70, 126, 136].

One of the major complaints by CRDP wearers is the lack of denture retention and stability [21, 83, 105, 110]. Jacobson and Krol [46], regarding denture retention, have stated: *“This property provides psychologic comfort to the patient. If a CRDP is easily dislodged during speech or eating, the embarrassment experienced can be mentally traumatic. A retentive CRDP contributes dramatically to patient acceptance of the finished prosthesis”*.

Retention of denture bases (DBs) has been attributed to combined-action of the following factors: (1) Interfacial surface tension; (2) capillary action; (3) adhesion, which is the attraction of saliva to the denture and tissues; (4) cohesion, which is the attraction of the molecules of saliva to each other; (5) saliva viscosity and film thickness; (6) negative atmospheric pressure; (7) the effects of gravity on the mandibular CRDP; and (8) the square of surface area [7, 19, 25, 32, 46, 124]. The forces of some of former factors are at a maximum when there is an adequate border seal and an intimate fit of the DB tissue surface to the underlying oral mucosa [27, 36, 80].

In this context, the critical role of a good posterior palatal seal (PPS) must be mentioned. PPS can be defined as the seal area at the posterior border of a maxillary removable dental prosthesis [121]. Accordingly, maintaining contact to the oral tissues during denture function or soft palate movement through completion of border seal is of particular importance [18, 37, 46, 50].

## 1.2 Polymethylmethacrylate resin as a denture base material

Polymethylmethacrylate (PMMA) resin was introduced as a DB material in 1937 [51, 113]. Since then, PMMA acrylic resin has dominated the field of DBs construction. This has been ascribed to its favorable physical and esthetic characteristics, material's availability, comparatively low cost, and the relative ease

with which PMMA may be processed, adjusted, or repaired [3, 4, 39, 73, 79, 92, 125, 129, 135].

### **1.2.1 Prosthetic applications of PMMA acrylic resins**

PMMA acrylic resins have been often applied in prosthetic dentistry such as fabricating of artificial teeth, dentures, impression trays, record bases, temporary crowns and maxillofacial prostheses. Thus, it can be, nearly, stated that there is almost no prosthetic procedure which is carried out without employing PMMA acrylic resin products [15, 24, 26, 92, 126].

### **1.2.2 Physical form, composition and polymerization of common-used DB acrylic resin materials**

The majority of DB acrylic resins are, commonly, supplied in a powder-liquid form [89]. Heat-cured (HC), cold-cured (CC) and microwave-cured (MC) PMMAs fall into this powder-liquid form.

#### **1.2.2.1 Powder**

Most of DB acrylic resins consist, predominantly, of PMMA beads modified with small increments of methacrylate copolymers. The powder also contains an initiator such as benzoyl peroxide to initiate the polymerization after blending the monomer liquid with the powder [109].

Pigments are added to produce the various tissue-like shades. Zinc or titanium oxides are used as opacifiers. Synthetic pigmented fibers are usually added to obtain the minute blood vessels appearance of oral mucosa. Plasticizers may be incorporated in the powder or the monomer in order to produce a tougher material [24].

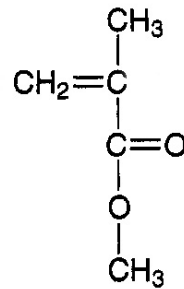
#### **1.2.2.2 Liquid**

Methylmethacrylate (MMA) monomer (Fig. 1) [24] is the major component of the liquid, but other monomers also may be added to the liquid [15, 24]. Inhibitors like hydroquinone are added to prevent premature polymerization of the monomer and, consequently, give the liquid prolonged shelf life [89, 109]. In cold-cured (CC) acrylic



resins activators like tertiary amines, barbituric acid derivatives are included in the liquid [15, 103].

Cross-linking agents such as ethyleneglycol dimethacrylate (EGDMA) are added to the monomer in order to obtain polymers characterized by a greater resistance to crazing, higher stiffness and less degree of solubility and water sorption [4, 109].

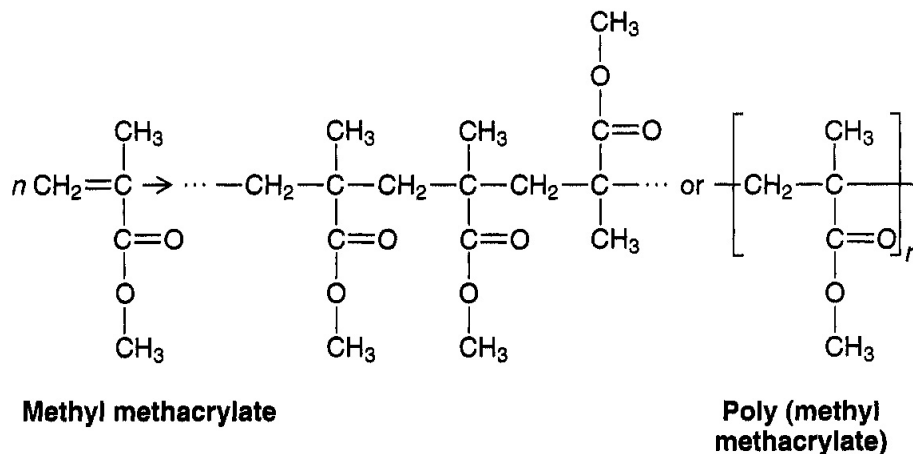


**Methyl methacrylate**

Fig. 1 – Methylmethacrylate monomer molecule

### 1.2.3 Polymerization reaction

In general, acrylic resin polymers are high molecular weight polymers, have a chain-like molecular structure and composed of small units called: Monomers [70]. Polymerization process is defined by the chemical linking of the monomers to build up polymers. PMMAs polymerization falls into the free-radical addition reaction which occurs with monomers containing carbon-carbon double bonds (Fig. 2) [24].



**Methyl methacrylate**

**Poly (methyl methacrylate)**

Fig. 2 – PMMA chain formation

This reaction may be activated by either heat, chemical activators, or radiation and traces of peroxides which lead, consequently, to the decomposition of the organic peroxide and formation of the free-radicals [26, 70, 126]. Usually, in heat-cured (HC) acrylic resins, decomposition of peroxide is activated by heat, however, in CC acrylic resins a chemical activator is required to trigger this process at room temperature [82]. The polymerization reaction is initiated when the free-radical reacts with a monomer molecule causing opening of one double bond which, in turn, produces another reactive free-radical molecule capable of further reaction with further double-bonded monomer molecules [26, 29, 54]. Compared to HC acrylic resins, CC types do not reach the same degree of polymerization and they have a higher residual monomer content [15, 26].

It has been reported that most of the residual monomer in the CC acrylic resins undergoes a post-processing polymerization. This delayed polymerization occurs mostly during the first week of 37°C water storage. Contrastly, the HC acrylic resins do not display a post-processing polymerization [10, 67, 103, 108].

#### **1.2.4 Modified DB acrylic resins**

Many modifications have been undertaken to improve the physical properties, durability, handling characteristics, and reducing the processing time of PMMA resins. This has led to the introduction of high-impact strength, and rapid HC acrylic resins [24, 49, 70, 73, 79, 90, 126].

### **1.3 Development of injection-molding technique for processing DB acrylic resins**

Compression-molding (CM) of PMMA has been the conventional processing method of DB materials [11, 30, 55, 90, 111]. Because of the undesirable dimensional changes that occur during processing by this method [3, 56, 65, 79, 128, 131], attempts to overcome them have led in 1942 to the development of the injection-molding technique (IM) for introducing the DB material into the mold [96]. Unfortunately, this technique, in that time, did not gain popularity [53], as injection-molded dentures were less accurate than compression-molded ones [3, 131].

During the following years there have been continued efforts to develop the injection technique and a continuous IM method, the SR-Ivocap system, has been

introduced [102]. Early reports on the SR-Ivocap system demonstrated favorable results regarding the magnitude of dimensional changes [11, 66, 104, 123]. Subsequently, a number of dental manufacturing companies have introduced their respective IM systems and, thereby, the method is more commonly used [81, 87, 127].

The currently available acrylic resin injection systems used in denture fabrication vary in design, materials, and processing procedures [100]. Claims were made for improved occlusal contact integrity, dimensional precision, reduced porosity, reduced fabrication time and costs as well as reduced hygienic problems related to contact with MMA monomer [43, 79, 81].

Technically speaking, the flask is closed and clamped before filling the mold with the favorable DB material. In terms of injection procedure, there is a hollow sprue which connects the mold space to an external opening on the flask and high-pressure-providing injection equipment is utilized to inject the mixed DB acrylic resin when it reaches the proper consistency through this opening. Some IM systems have, additionally, a vent opening on the furthest side from the injection-side. The high-pressure injection is, in most of injection systems, maintained during the curing cycle and as polymerization proceeds and shrinkage occurs, an additional fresh non-polymerized material is supplied from a reservoir through the sprue, so that the polymerization shrinkage is compensated for. IM is employed in HC, CC, and MC acrylic resins [24, 34, 53, 81, 115, 123].

#### **1.4 Dimensional precision of DB acrylic resins**

The dimensional accuracy and stability of the DB during processing and in service is important for obtaining a close fit to the soft oral tissues [69, 93, 122] and, consequently, gaining a reasonable denture retention, attaining a correctly functioning denture, maintaining healthy oral tissues and ensuring the comfort and satisfaction of the patient [28, 30, 54, 64, 66, 97, 138]. However, PMMA acrylic resin DBs undergo unavoidable dimensional changes during processing, mainly, thermal shrinkage and polymerization shrinkage. Furthermore, they expand when they are stored in an aqueous environment and contract upon dehydration [10, 38, 51, 82, 84, 93, 99, 107, 109, 115, 119, 125, 132, 133, 137].

It has been revealed that oral tissues could relatively adapt with a limited deviations from the desired dimensions of the processed DB, but this does not mean

that they stay healthy and normal under conditions in which the misfit exceeds 1 mm or more [63, 88, 97]. On the other hand, an ill-fitting denture can lead to fracture of the denture as a result of fatigue [13, 70]. Moreover, processing dimensional changes may alter the interocclusal contacts of the CRDPs [12, 35] which could cause an induced malocclusion which, in turn, needs more laboratory time-consuming procedures to be adjusted [127].

## **1.5 Factors influencing the dimensional precision of DB acrylic resins**

### **1.5.1 Polymerization and thermal shrinkage**

When MMA is converted to PMMA it undergoes a volumetric shrinkage of around 20-21% [9, 26, 54, 69, 70, 91, 125, 126]. Usually, the ratio of polymer to monomer utilized in the preparation of PMMA acrylic resins is 2.5-3:1, thus, blending the monomer with the polymer produces a volumetric polymerization shrinkage which ranges between 5-9% [24, 26, 54, 70, 91, 126] but it is generally accepted that the average value is 7% [4, 39]. Accordingly, it can be theoretically extrapolated that the linear shrinkage should be in order of 1.5-2 % [126], however, the values span over a range from 0.1 to 0.6 % with the CC types of DB acrylic resins showing, generally, less shrinkage than the HC ones when the linear measurements are carried on denture-like specimens [3, 38, 72, 78, 114, 131, 135, 137]. In this context it should be, however, noted that a part of the polymerization occurs after the acrylic resin has reached a solid state, resulting in formation of internal stresses in the resin rather than additional shrinkage [24].

Some researchers suggested that polymerization shrinkage contributes slightly to the net linear shrinkage of HC acrylic resin DBs [32, 50, 134] and this, thereby, highlighted the important role of glass transition temperature ( $T_g$ ) and coefficient of thermal expansion (CTE) of the acrylic resins. Acrylic resins, when heated, are transformed from a glassy or rigid state to a rubbery or flexible state. The temperature of this transition is called the glass transition ( $T_g$ ) [48]. At this temperature molecular motions are facilitated and whole chains are capable of moving, thus acrylics are easier to deform above  $T_g$  temperature [9, 70]. Therefore,  $T_g$  temperature has a considerable impact on the dimensional stability of dentures fabricated from acrylic resins [69]. CC resins have generally lower  $T_g$  values than those for HC materials [69, 70].

The temperature change from processing temperature to room temperature indicates the importance of the coefficient of thermal expansion (CTE). Acrylic resins have relatively high CTE of about  $80-81 \cdot 10^{-6} \cdot ^\circ\text{C}^{-1}$  compared with dental gypsums which possess a CTE values ranging between  $10 \cdot 10^{-6} \cdot ^\circ\text{C}^{-1}$  to  $25 \cdot 10^{-6} \cdot ^\circ\text{C}^{-1}$ . Consequently, this large difference between the CTEs of gypsum and acrylic resin can lead to thermal linear shrinkage in the HC acrylic resin of about 0.42% to 0.56% [54, 66, 91] when the flask is cooled to room temperature. Accordingly, CTE plays an important role in the fit of DBs [92].

The influence of the CTE is remarkably observed, particularly when HC acrylic resins are used. The difference in the CTEs between the DB material and the surrounding gypsum materials is responsible for the development of internal stresses within the processed denture when the flask is cooled to room temperature. During the cooling phase, acrylic resin and the gypsum material experience a thermal shrinkage. The magnitude of the resin's shrinkage will depend on the difference between the T<sub>g</sub> of the resin and room temperature. It is evident that as long as the acrylic resin temperature is above T<sub>g</sub>, which means that it is still soft, it will shrink thermally with the stone cast, which, of course, has a different CTE. As the temperature falls down to the T<sub>g</sub>, resin starts to harden. Consequently, stresses are formed as cooling proceeds, because the DB material is forced to comply with the shape of the stone cast, in spite of the variations in CTEs, and in this case the thermal contraction of the acrylic resin is restricted and, thus, will increase the internal stresses. Release of these internal stresses may, later, cause dimensional changes and denture warpage (misfit) [20, 24, 50, 52, 69, 70, 126].

It is believed that using CC acrylic resins produce DBs that are relatively free of internal strain, and therefore they may be dimensionally more accurate than DBs processed using HC material [24, 28, 72, 86, 87]. This has been attributed to the facts that lower temperatures are involved in the curing of CC acrylic resins [3, 126, 130], and that they are cured below their T<sub>g</sub> temperature [69]. Accordingly, it has been stated that the processing shrinkage of HC acrylic resin was caused mainly by thermal shrinkage [3, 52], whilst the shrinkage of CC acrylic resin was caused mainly by polymerization shrinkage [69].

### **1.5.2 Factors related to the DB material and processing procedures**

The exact composition of a DB acrylic resin is proprietary and is not disclosed by the manufacturers [1, 82]. Therefore, it can be assumed that differences in materials may also exert an effect on the dimensional behavior of these acrylics [23, 53]. In contrast, it has been concluded that the influence of employing different acrylic resin brands on the dimensional precision seemed to be of minor relevance [127].

The majority of dimensional changes that occur on DBs take place during their curing process [120, 135]. Conflicting results have been reported on the effect of curing cycle on the shrinkage of acrylic resin DB materials. Some authors have mentioned that either short curing cycle that includes subjecting the DB material to boiling temperatures or rapid cooling tend to increase the magnitude of dimensional changes [43, 52, 71, 106]. Others have stated that the curing cycle seems to have little impact on the processing shrinkage. However, the rate of cooling of the flask has a substantial effect on the observed shrinkage of dentures [20]. Firtell et al. [32] and Polychronakis et al. [93] have pointed out that some rapid-cured DB materials, which can be polymerized in boiling water for a short time, exhibited promising results in regard to dimensional precision.

With respect to the molding methods, it has been reported that the molding technique is a significant factor in regard to the dimensional changes [2, 43, 58, 81, 82, 86, 101, 114, 127]. In contrast, others [5, 35, 45, 53, 57] have presented that no significant dimensional differences were recorded in respect to the molding technique.

### **1.5.3 Water sorption**

Dental acrylic resins tend to absorb water and to expand slowly over a period of time [14, 75, 135]. This corresponding expansion is expressed in three dimensions and is of considerable importance [77, 99, 132]. Expansion of the acrylic resin is proportional to the time of water immersion until equilibrium is reached [29]. The average equilibrium water content (water content at saturation), however, should not exceed the value of  $32 \mu\text{g}/\text{mm}^3$  [70]. Water absorption could also release the inherent stresses emerged during processing of the acrylic resin, primarily the HC, and possible change in the shape of the denture might occur [57, 99].

Diffusion coefficient governs the rate of water sorption and the time needed to attain saturation. The diffusion coefficient is extremely temperature-dependent but

has no effect on the equilibrium (saturation) water content [14]. The amount of water sorption depends on the material type [78, 118], the thickness of the material [101], and the residual monomer content [29, 47]. Takahashi and coworkers [119] revealed that HC acrylic resins take a longer time than the CC acrylic resins for water absorption to reach saturation because of their lower diffusion coefficient of water. Moreover, it has been demonstrated that average expansion of the CC resins during service, i.e. after processing, was slightly greater than that of HC materials, and this was attributed to the larger water absorption exhibited by CC resins in comparison to that of HC materials [78].

Huggett et al. [43], Nogueira et al. [81] and Venus and associates [127] reported that significant dimensional changes (expansion) of acrylic resins were recognized between the two phases – before and after water immersion. Whereas, Anderson et al. [2] stated that after storage in water for 30 days, acrylic resin samples demonstrated expansion, however, the increase in the dimensions was not statistically significant. In any case, however, the vast majority of authors believe that processing dimensional changes (shrinkage) of DB acrylic resins could be, partly, compensated for by water absorption [15, 101, 113, 115, 132, 135].

#### **1.5.4 Other factors contributed to the dimensional changes of DB acrylic resins**

Regardless of the foregoing factors influencing the dimensional accuracy and stability of DB acrylic resins, it should be kept in mind, that other factors might be responsible for the deviations in dimensional accuracy, such as the powder/liquid ratio of DB material [32, 54, 72], type of the denture (maxillary or mandibular) [11, 77, 131], palate morphology and residual ridge's height [37, 50, 57, 59, 86, 115], type of cast dental stone [116, 117], denture thickness [20, 50, 60, 101, 131], presence of artificial teeth [6, 8, 44, 127], and the manner of finishing and polishing of the processed denture [45, 62], and isolation of stone surfaces [66].

#### **1.6 Determination of dimensional precision**

Linear measurements have been generally used to determine the dimensional changes occurring in processed DB acrylic resins. Measuring microscopes, optical comparators, vernier calipers and computerized coordinate measuring techniques

were employed to evaluate the linear dimensional changes because of their availability and reliability [2, 41, 43, 53, 79, 81, 82, 102, 114, 127].

However, it has been pointed out, that dimensional changes tend to occur in three dimensions rather than in only one plane [12, 28]. Consequently, this has led to the idea that there could be a reasonable reason to evaluate the dimensional accuracy and stability of DB materials by using other parameters than the linear parameter. Accordingly, it was believed that the investigation of volumetric dimensional changes would be of a valuable importance [100]. Moreover, it has been already mentioned that irrespective of the curing method or type of acrylic resin employed, the missfit of the denture will be evident as soon as the cured dentures are deflasked and removed from the cast. This was considered as a major disadvantage of this material [20, 57, 71, 82, 94, 120, 131].

Measuring linear dimensional changes may over-simplify the complex changes that occur due to the polymerization, cooling, water sorption and release of stress [79]. Additionally, linear or volumetric dimensional changes measurements might not be sufficient to interpret the misfit recognized in many clinical situations. Therefore, distortion of the DB adaptation has also been considered as an important factor in the appreciation of processing dimensional changes [60, 138].

The misfit of processed denture is mostly marked at the PPS, especially at the midline area [3, 5, 50, 57, 61, 74, 94], which may result in deterioration of the PPS and, thus, reduced denture retention [18, 91]. Due to the vitality of this region, many researchers have investigated the discrepancies involved in denture processing at the PPS area [57, 61, 66, 85-87, 95, 114-116, 127].



## **1.7 Aim of study**

The dimensional accuracy and stability of various denture base (DB) acrylic resins processed by different injection-molding (IM) methods have not been extensively studied.

Most of the former studies have generally focused on measuring the dimensional precision of the injection-molded DB acrylic resins in one perspective, i.e. either the PPS distortion or the linear dimensional changes of anatomic or non-anatomic shape specimens. The fact is that dimensional changes are seen throughout the processed acrylic resin, which means that a comprehensive study including employment of multiple dimensional change measuring methods would interpret the dimensional behavior of the investigated DB materials.

Therefore, the purpose of this study was to investigate the dimensional precision of DB materials processed by their respective IM techniques by conducting and comparing the linear, volumetric, and PPS distortion measurements over a three months observation period while the specimens are stored in 37°C temperature distilled water.

The two null hypotheses were: Firstly, there is no significant difference in either the linear or volumetric dimensional changes between the various acrylic resins processed by employing their specific IM systems, secondly, there is no significant difference in PPS distortion between the DBs prepared from various acrylic resins processed by using their specific IM systems.

## 2 Material and Methods

Six IM acrylic resins were selected for evaluation. The materials, manufacturers, proportions of powder to liquid, fabrication system, the type of polymerization, and the polymerization parameters are shown in Table 1.

**Table 1 – Description of tested DB materials.**

Product	Abbreviation	Manufacturer	Batch no.	Polymer: monomer Ratio	Fabrication system	Polymerization type	Polymerization parameters
IvoBase Hybrid	IBHY	Ivoclar Vivadent AG, Schaan, Liechtenstein	NM0188	34g:20ml	IvoBase Injection System	Auto-polymerizing	Electromechanical injection, 35 min, initiating temperature 40°C, dry heat
IvoBase Hi Impact	IBHI	Ivoclar Vivadent AG, Schaan, Liechtenstein	NM0157	30g:20ml	IvoBase Injection System	Auto-polymerizing	Electromechanical injection, 50 min, initiating temperature 40°C, dry heat
SR Ivocap Hi Impact	ICHI	Ivoclar Vivadent AG, Schaan, Liechtenstein	N35171	20g:30ml	SR Ivocap Injection System	Heat-polymerizing	Pneumatic injection, 35 min in boiling water
FuturaGen	FUT	Schütz Dental Gmbh, Rosbach, Germany	2010006210(powder) 2010005960(liquid)	35g:16ml	UNIPRESS Injection System	Auto-polymerizing	Manual injection, 30 min, 30°C-40°C, bench-curing
PalaXpress	PLX	Heraeus Kulzer Gmbh, Hanau, Germany	011095(powder) 010471(liquid)	30g:15ml	Palajet Injection System	Auto-polymerizing	Pneumatic injection, 30 min, water bath 55°C, pressure-pot 2 bar
Lucitone 199	LUC	Dentsply International Inc., York,PA,U.S.A.	100506(powder) 100406(liquid)	21g:10ml	Success Injection System	Heat-polymerizing	Pneumatic injection, water bath 90 min at 72°C and 30 min in boiling water

This investigation consisted of two parts: In the first part a specimen with a simple non-anatomic shape was employed for the evaluation of the linear and volumetric dimensional change of the acrylic resin itself. In the second part a DB-like specimen was used to investigate the PPS distortion of the DBs.

### 2.1 Linear and volumetric dimensional change evaluation

#### 2.1.1 Specimen preparation

In order to fabricate the specimens, a master die was constructed using Invar\* metal ( $CTE \leq 2 \mu m/^{\circ}C$ ) with the dimensions given in Fig. 3.

\*Invar - Controlled Expansion Alloy, Goodfellow, Ermine Business Park, Huntingdon England.

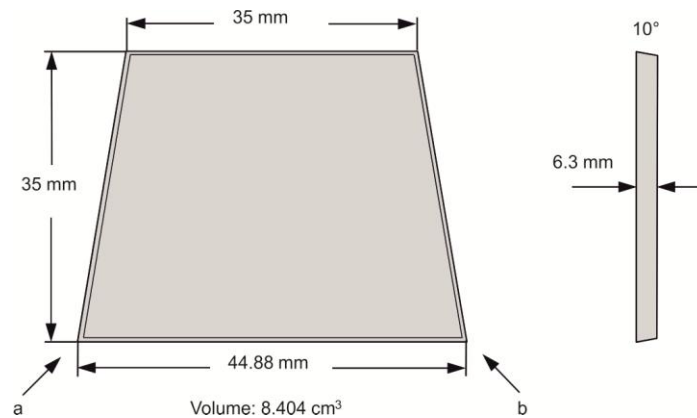


Fig. 3 – Dimensions of the master die used in this study. Left and right diagrams represent the top and side views of the master die, respectively. “a” and “b” indicate the reference points for linear dimensional measurements.

The shape of the master die, double-sided isosceles trapezoid, enabled direct comparison of linear and volumetric dimensional changes. The vertical walls were fabricated with a 10-degree convergence to facilitate removal of the die from the investment after the flasking procedure.

To compare the dimensional changes of the specimens, a total of 36 specimens were prepared with 6 specimens for each resin (n=6). A wax injection sprue was attached to the shortest (anterior) side of the master die. Sprue length and diameter were determined according to manufacturers’ instructions for each studied DB resin. Hereinafter, the master die was directly invested in the denture flask [1, 2] by pouring the stone (Dura-Halbhartgips grün, Siladent Dr. Böhme & Schöps, Goslar, Germany) into the lower half of the flask and embedding the master die in the stone of the lower half of the flask at the same height as the level of flask edge. Dental stone mixing procedure was accomplished by using the manufacturer’s recommended water/powder ratio (40ml/100g).

After the stone of the lower half of the flask had set (45 minutes), the master die and the exposed stone surfaces were isolated with Isofix 2000 separator (Isofix 2000 No.1720, Renfert, Hilzingen, Germany). Subsequently, the top half of the flask was placed on the bottom half, ensuring complete intimate contact and closure of the halves, and filled with the same stone. All flasks, which were used in our study to prepare specimens, were poured by using vacuum-spatulated stone according to manufacturer’s recommendations and a single pouring technique. After the stone had set (45 minutes), the flask was heated and the two halves of the flask were separated

to flush out the wax sprue, and to remove the master die. Two layers of sodium alginate (ISO-K blau, Candulor, Wangen, Switzerland) were applied to the exposed stone surfaces and allowed to dry. Thereafter, the flask was clamped and the powder/liquid mixture of DB material was prepared to be polymerized. The investigated DB resins were mixed according to the respective manufacturer's instruction. The curing cycles were also set in accordance with the manufacturer's instructions. After the completion of processing, the flask was cooled to room temperature ( $24^{\circ}\text{C} \pm 1^{\circ}\text{C}$ ). The IM systems employed in this investigation are illustrated in Fig. 4 – A to E.

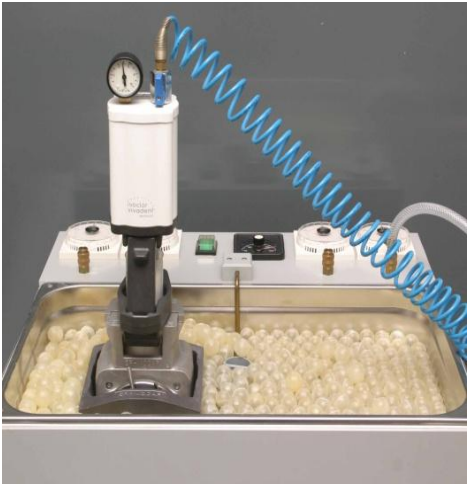


Fig. 4 – A: SR Ivocap injection system



Fig. 4 – B: Palajet injection system

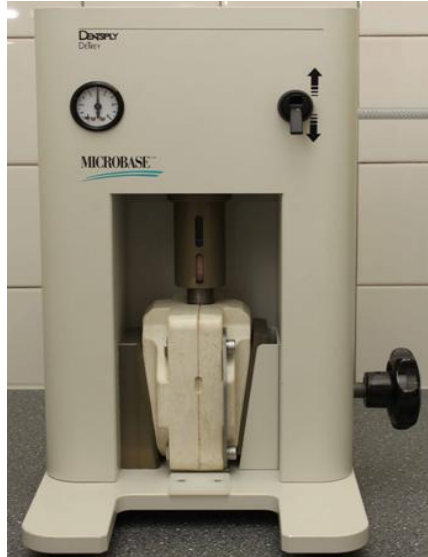
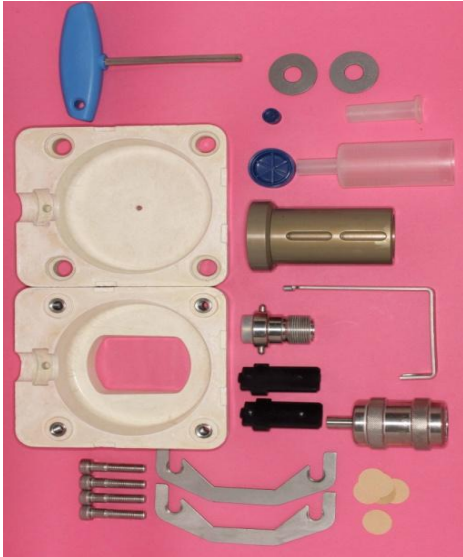


Fig. 4 – C: Success injection system



Fig. 4 – D: UNIPRESS injection system



Fig. 4 – E: IvoBase injection system

Following processing, the specimen was carefully removed from the stone mold, and the injection sprue was sectioned by means of a saw (Isomet 1000 precision saw; Buehler, LakeBluff, IL, USA), leaving the specimen's injection side without any sprue remains (Fig. 5).



Fig. 5 – A processed specimen

It should be mentioned that manufacturers' instructions for each injection system, with respect to the predetermined water temperature and time, which has been employed for the wax elimination procedure, were precisely followed. Furthermore, the prerequisites concerning the application of the separating medium to the stone surfaces were taken into consideration. In other words, attention had been paid to the appropriate time for the application of the separating medium in relation to the temperature of the flask.

The investing procedures, as well as, the processing procedures for all investigated materials were carried out in one uninterrupted session so that no delay between investing and processing occurred [12]. All specimens within each resin group were made from the same batch number and stored in ( $37^{\circ}\text{C} \pm 1^{\circ}\text{C}$ ) distilled water for 1, 30, and 90 days before being tested.

### **2.1.2 Measurements**

The measurements obtained from the metal die were used as the baseline readings, and all values were calculated with these measurements as the starting point. All measurements were carried out by the same investigator. At each time interval the specimens were removed from the water and dried by blotting with absorbent tissue.

### 2.1.2.1 Linear dimensional change measurements

Using a digital caliper (Orion, Hahn + Kolb Werkzeuge, Stuttgart, Germany), that read to an accuracy of 0.01 mm, three repeated readings of the distance between the two reference points a and b (the tips of the 2 sharp corners at the metal die) were recorded by the investigator, and the average of the readings was considered the baseline reading ( $L_0$ ). For this purpose, an assisting-impliment was constructed of plastic material to stabilize and support the metal die during conducting the linear measurements.

The prepared specimens were measured following the same previously described procedure at each protocol interval, and the mean of the three readings was used as the measurement ( $L$ ). Subsequently, the percentage of the linear dimensional change ( $\Delta L$ ) of the studied DB resins was calculated as follows:

$$\Delta L(\%) = 100 \frac{L - L_0}{L_0}$$

### 2.1.2.2 Volumetric dimensional change measurements

Archimedes' principle was used to determine volumetric dimensional changes. This has been achieved by using an electronic hydrostatic balance (UW620H, Shimadzu Corporation, Japan), which is accurate to the nearest 0.001 g and consists of combination pans (upper and lower), pan frame, tank, tank table, and frame supporters. The electronic hydrostatic balance can determine not only the weight but also the density of specimens based on the buoyancy of a material in fluid, which means the weight of displaced fluid. Solid specimen submerged in the medium liquid, which is usually distilled water, receives buoyancy that equals to the weight of the medium liquid of the specimen volume. When the weight of solid specimen in air and the weight in the medium liquid are known, the density of the solid specimen can be obtained with the density of the medium liquid. The balance computes the solid specimen's density ( $\rho$ ) according to the below given expression, and displays the result. This expression is derived from Archimedes' principle:

$$\rho = \frac{W_a}{W_a - W_l} \rho_l$$

$W_a$ : Solid specimen weight in air,  $W_l$ : Solid specimen weight in the medium liquid,  $\rho_l$ : Density of the medium liquid.

Firstly, the master die has been weighed on the upper balance's pan. Three weight readings were obtained, and their mean was considered the baseline reading ( $W_0$ ). Secondly, the die was removed from the upper balance's pan and placed in the lower balance's pan immersed in distilled water and the displayed apparent density was noted. Three density readings were obtained, and the mean was considered the baseline reading ( $D_0$ ). This procedure was done with extreme care to ensure that no air bubbles adhered to the die's surface. The volume of the die was calculated as follows:

$$V_0 = \frac{W_0}{D_0}$$

The calculated volume of the metal die was used as the baseline reading ( $V_0$ ). The prepared specimens were measured following the same previously described procedure at each protocol interval, and the mean of the three readings was used as the measurement ( $V$ ). Subsequently, the percentage of the volumetric dimensional change ( $\Delta V$ ) of the studied DB resins was calculated as follows:

$$\Delta V(\%) = 100 \frac{V - V_0}{V_0}$$

## **2.2 PPS distortion evaluation**

### **2.2.1 Specimen preparation**

In terms of determining the PPS distortion, a total of 60 experimental maxillary DB-like specimens were prepared with ten specimens for each resin ( $n=10$ ).

For the fabrication of the DBs, a test-specific idealized Invar master model, simulating nearly a maxillary edentulous jaw without anteriorly continuous ridge (premaxilla) and with a flat palate form, was constructed. The master model was free of undercuts; the slopes of vestibular and palatal sides of the ridge were machined at  $84^\circ$  from the horizontal and converging toward the crest of the ridge. This inclination of the ridge slopes allowed, later, an easy removal of test specimens without warping them or destroying the stone casts.

To enable determining the magnitude of the PPS distortion of the studied DB resins, a shallow groove of 3 mm width and 8.5 mm length was precisely drilled into the midline of posterior palatal side on the model and extended anteriorly from the posterior edge of the master model such that the groove's frontal-formed edge



located directly at the prospective posterior palatal border of the DB; in other words, the examination field (Fig. 6, Fig. 7).

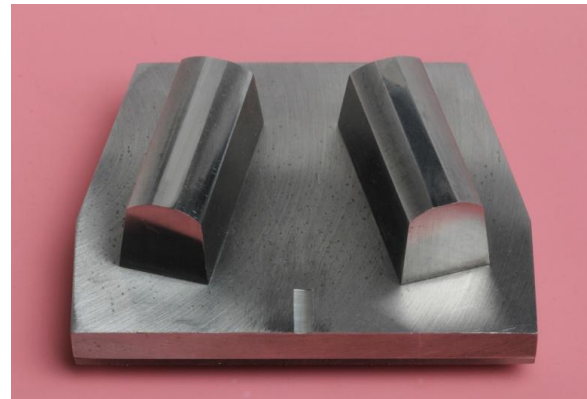
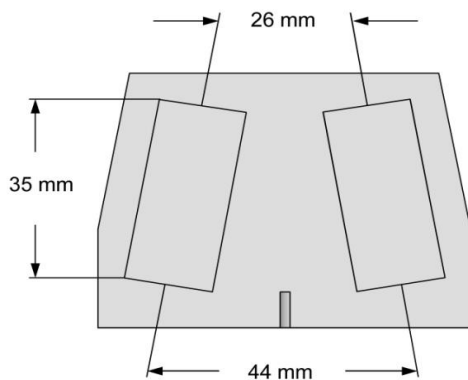


Fig. 6 – Schematic view of the dimensions of the master model (left)

Fig. 7 – The master model used in this investigation (right)

The master model was duplicated by employing the silicone mold duplication technique [95]. In order to optimize the duplicating procedure, an aluminum custom flask was manufactured. This flask had a cylindrical shape which measured 44 mm in height, 9 mm walls thickness and 100 mm internal diameter. To obtain an adequate retention for the duplicating material, four screws laterally cross-like distributed and four basically drilled holes of 16 mm diameter were provided. These holes served also the pouring process of the duplicating material.

The duplicating procedure was carried out as follows: the master model was placed on a glass slab and the flask was positioned over the model in a manner that the flask base is upwards directed and the flask walls surrounding the model, which was, axiomatically, in the center of the flask. The intimate contact of the flask edges to the glass slab was inspected, and to exclude any possible subsequent flow out of the duplicating material, a molten wax was utilized to seal the outer borders of the contact area.

By means of the mixing and dosing unit (DG1, Degussa AG, Hanau, Germany), the duplicating compound (Deguform, DeguDent GmbH, Hanau, Germany), which is a two-component addition-curing silicone with a linear contraction of 0.08% [95], was poured into the flask through the prepared holes until the complete fill of the flask. Excess material was allowed to run over the holes to achieve an additional retention in this area. The duplicating silicone material was allowed 45 minutes in room temperature to set. After the setting of the material, the master model was removed by applying a light stream of compressed air and the

duplication, which is now called "duplicate mold", was left for 15 minutes to recover from any possible deformation that could be occurred. In this way, 61 duplicate molds were obtained from the master model (Fig. 8, Fig. 9).



Fig. 8 – The aluminum custom flask (left)



Fig. 9 – The duplicate mold (right)

Subsequently, each duplicate mold was treated with a surface-tension reducer solution according to manufacturer's instructions (Debubblizer, Kerr Italia S.r.l., Salerno, Italia). Then, the stone casts were prepared by pouring a mix of type III dental stone (Moldano, Heraeus Kulzer GmbH, Hanau, Germany) into the duplicate mold. Dental stone mixing procedure was accomplished by using the manufacturer's recommended water/powder ratio (30ml/100g) and spatulating under vacuum.

The poured stone was allowed 45 minutes at room temperature to set. After setting of the stone material, the stone cast was removed by applying a light stream of compressed air (Fig. 10).

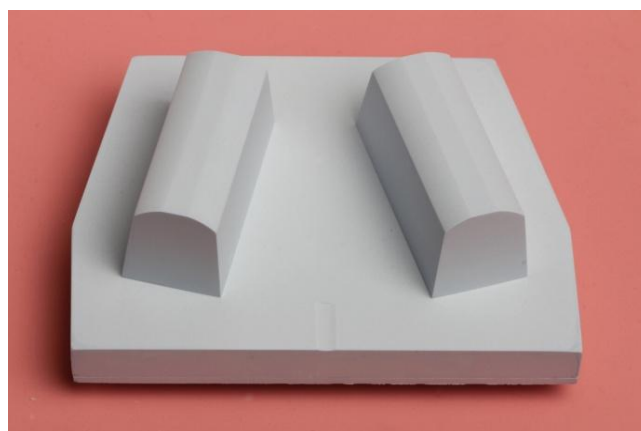


Fig. 10 – The stone cast

In this manner, 61 identical stone casts were fabricated. The base of each stone cast was lightly ground by using water-cooled trimmer to eliminate the fine irregularities, so that ensuring that all stone casts had a similar base thickness. Later on, one stone cast was arbitrarily selected for the subsequent wax-up and duplicating mold fabrication procedures and was designated as the master stone cast. The remaining 60 stone casts were randomly assigned into the predetermined six test groups. Thereafter, all stone casts in each group were coded and numbered for identification according to each investigated DB material.

Next, a simulated maxillary DB was fabricated in wax. Two 1.5 mm thick baseplate wax sheets (Modelling wax pink, Pluradent AG & Co KG, Offenbach, Germany) were gently adapted to the master stone cast to prevent, as much as possible, thinning the material in any region. In this manner a 3 mm thick wax-up DB was made, which covered the ridges, the extended flat area between them, limited dorsally by the frontal edge of the drilled groove and supplied anteriorly with three wax injection sprues, which finally combined together to form a main injection sprue. This wax-up together with its stone master cast represented the master wax-up pattern which was utilized to obtain replicas of waxed up DBs of identical thickness ( $\pm 0.2$  mm) for the rest of the stone casts.

Subsequently, a duplicating material (Speedy Wax Transpaduplisil 101, Zahntechnik Norbert Wichnalek, Augsburg, Germany) was employed following the manufacturer's instructions to make a mold from the master wax-up pattern. For this purpose, a Plexiglas rectangular custom container was prepared. This custom container provided support and rigidity for the duplicating material. The master wax-up pattern was placed inside the container and the duplicating material was handled and poured following the manufacturer's recommendations. After the duplicating material had completely set, the container was opened and the master wax-up pattern was retrieved (Fig. 11, Fig. 12).



Fig. 11 – The Plexiglas custom container (left)



Fig. 12 – The wax-up duplicating mold (right)

Later on, each group of stone casts, was waxed up as follows: A stone cast was placed in the mold, thus, this resulted in creating a space, where the master waxed up DB has already occupied, which is to be now filled with the injected molten wax. The container, which includes the mold and the stone cast, was closed and held firmly while 70°C molten wax (Speedy Wax Injektionswachs 70 grün, Zahntechnik Norbert Wichnalek, Augsburg, Germany) was being injected under a pressure of 1.3 bar by means of wax-injector device (Speedy Wax Injektor 1500 M, Zahntechnik Norbert Wichnalek) through the main injection sprue hole. After the wax has been allowed to cool at room temperature for two hours, the container was opened and the recently waxed up stone cast was recovered from the mold (Fig. 13, Fig. 14).

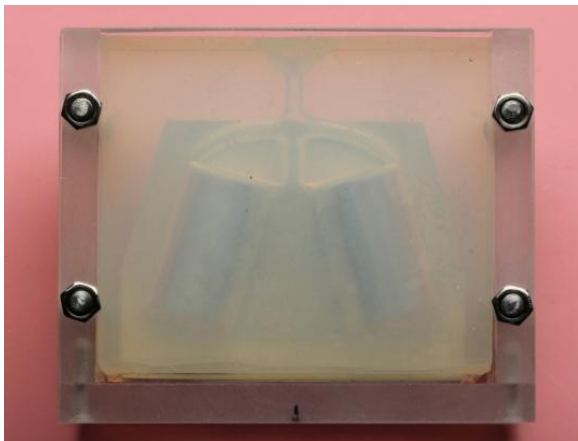


Fig. 13 – The waxed up stone cast inside the mold (left)



Fig. 14 – The recovered waxed up stone cast (right)

Thereafter, the wax injection sprues were cut off at the appropriate position. Fit and border seal integrity of the waxed up DB on its corresponding stone was inspected and a slight refining procedure, if required, was carried out. Sixty waxed up DBs of identical thickness and contour on their representative stone casts were reproduced by injecting fluid wax into the mold. Although some variation in the thickness was evident, this was within small limits and apparently showed an acceptable reproducibility in the thickness of waxed up DBs.

Prior to carrying out processing procedures for each studied DB material, each group of the perfected waxed up stone casts was stored at room temperature for one week for stress relief within the wax [82]. Each group of completed waxed up stone casts was processed with one of the studied DB materials cured by using their respective IM system. Conventional dental laboratory procedures were used to fabricate the acrylic DBs. Each waxed up stone cast was soaked in water for 5 minutes prior to investing [40]. Investment, isolation of exposed stone surfaces, flask heating, wax eliminating, separating medium application, powder/liquid mixing, acrylic resin processing, and flask cooling were all conducted in a similar manner used in the first part of this investigation.

Following processing and deflasking, each specimen was with care visually inspected and the injection sprue was sectioned by means of suitable acrylic-finishing burs. Flashes, if any, were trimmed. Sixty DBs in 3 mm thickness were made following the manufacturers' recommendation. All specimens were placed in a plastic box filled with distilled water and covered with a well-fitting lid to minimize evaporation and stored in an incubator with the temperature set and maintained at ( $37^{\circ}\text{C} \pm 1^{\circ}\text{C}$ ) for 1, 30, and 90 days before being tested.

## **2.2.2 PPS distortion measurement**

### **2.2.2.1 The construction of experimental assembly**

In order to examine the PPS distortion between each fabricated DB and the master invar model under similar conditions at each time interval, a special assembly has been designed. This assembly permitted, mainly, the consistent orientation of the master model and, consequently, the reproduction of the same spatial position of the tested PPS area under the microscope lens.

The first component of this assembly composed of a cylinder-shape aluminum block of 58 mm height and 100 mm diameter which was milled in two stages: In the

first stage, a circular circumferential milling, 5 mm wide and 53 mm high, was performed. Consequently, a circular step of 5 mm width and 5 mm height at the basal side of the cylinder was formed. In the second stage, about 60% of the bulk of the aluminum cylinder, 5 mm above the step level, was milled off leaving a horizontal flat circular area (table), which measured a 10 mm thickness from the basal side of the cylinder, and an emerging vertical cylinder-section of 48 mm height with its flat side (internal side) orienting toward the center of the cylinder. The flat surface of the vertical cylinder-section enabled, later, the exact vertical alignment of the master invar model through the intimate fit of its base to the flat surface at each time interval for PPS distortion investigation.

The second component composed of a Perspex (Plexiglass) collar of 90 mm inner diameter, 5 mm wall thickness and 60 mm height. Then, the two components were assembled together by sliding the collar over the already milled aluminum cylinder and luting them together by using a solvent free 2-component epoxy resin adhesive (UHU plus endfest 300, UHU GmbH & Co. KG, Bühl/Baden, Germany). Following the setting of the adhesive material, a pneumatic cylinder-piston (Wabco Westinghouse 002 max 10 bar 522.601.025.0 14/88 Ø 12 S= 25) was horizontally aligned and firmly fastened to an already drilled hole into the collar's wall at an appropriate height. The pneumatic cylinder-piston was connected to a controlled pressurized-air supplier.

A rectangular aluminum plate which measured 50x10x5 mm in dimension was affixed in its central portion to the end of the plunger (piston). This pneumatic cylinder-piston along with the rectangular plate served, subsequently, the purpose of applying a bilateral load on the crestal surface of the DB and, consequently, holding the DB specimen in location onto the master model under a predetermined constant pressure of 5 N to avoid undue distortion [41, 60].

Additionally, the collar was provided with a water inlet which was placed in the lower portion of the collar and a water outlet which was placed in the upper portion of the collar and were connected to a thermocirculator (LAUDA CS 6; Lauda-Königshofen, Germany) which supplied the assembly with a continuous 37°C distilled water flow. This enabled obtaining a temperature-controlled investigating chamber.

The assembly's base was, hereafter, fixed on a flat plastic pan which was modified in a manner that its lower surface would fit to the upper surface of the base of a light microscope (Wild Makroskop M 420; Heerbrugg, Switzerland), so that the

prospective location of the investigated mid-PPS area was vertically positioned/repositioned directly beneath the microscope's lens center and, thus, is reproducible throughout all stages of evaluation. On the other hand, this has in turn ensured that the orientation for all of the tested specimens at the three time intervals was the same and there would not be a distortion of measurements as a result from obliquely viewed and taken images [59]. The assembly and the inspection of PPS distortion are shown in Fig. 15 and Fig. 16.

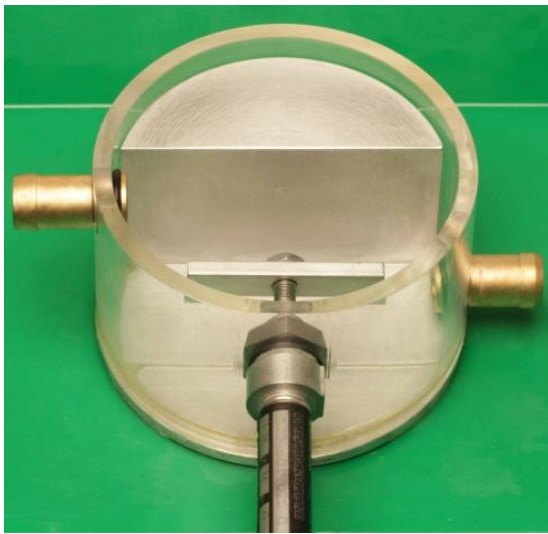


Fig. 15 – The used assembly (left)

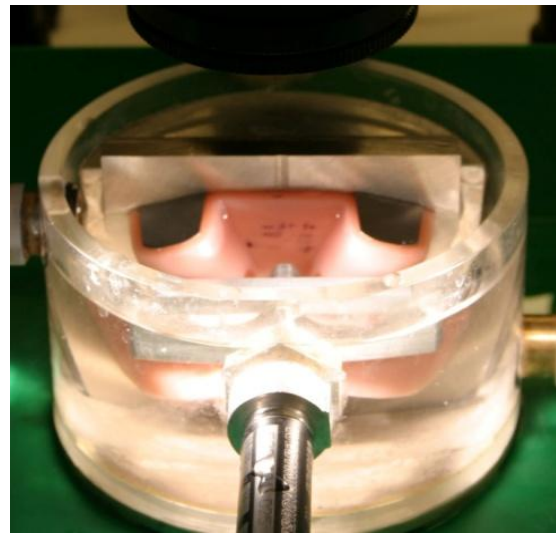


Fig. 16 – Inspection of PPS distortion of DB (right)

#### 2.2.2.2 Obtaining digital images

In order to determine the PPS distortion, the thermocirculator was switched on and the assembly's chamber was pre-heated with 37°C circulating distilled water for fifteen minutes, subsequently, the master model was laid vertically in the assembly's 37°C water bath for ten minutes, then, each tested DB was carefully seated onto the master model and, using fingers, a gentle contact between the terminal aluminum plate and the crestal surface of the DB was made, then, the pneumatic cylinder-piston was turned on.

The interface gap between the palatal tissue surface of the DB at the mid portion of the PPS region and the master model was viewed perpendicular to the measurement plane with light microscope (Wild Makroskop M420, Heerbrugg, Switzerland) at 70x magnification; the objective lens was set on the maximum 35x magnification and further equipped with a conversion objective 2.0x so that the total

obtained magnification was 70x. An auxiliary cold-light source (Zeiss CL 1500 ECO, Germany) was utilized to ensure obtaining the appropriate illumination of the tested field.

A digital camera mounted on the microscope's tube was used. The viewing procedure was carried out through its optical viewfinder window. By using the coarse and fine adjustment focus knobs, the microscope objective lens was set to the proper height which ensured the maximum visual focus on the targeted area. Two digital images were taken for each investigated DB at each time interval. This has been achieved by removing and replacing the specimen on the master model after taking the first digital image, since it has been believed that this would eliminate the DB's minor displacement errors during test procedures.

### **2.2.2.3 Preparing the Photoshop software**

Photoshop software (Ps Adobe Photoshop CS4 Extended, Version 11.0.0.0, Adobe Systems Incorporated, USA) was employed to measure the PPS distortion on the digital images. For this purpose, the software was firstly calibrated as follows:

A 2 mm optical microscope stage micrometer reading at 0.01 mm intervals (Leitz Wetzlar, Germany) was seated gently on the upper surface of the light microscope base. The microscope was set at the predetermined 70x magnification. Care was taken that the scale was located directly under the center of the microscope lens. The microscope lens height was managed so that the maximum focus of the scale was obtained. Then, using the same mounted digital camera a digital image was taken.

Subsequently, this digital image was transferred to the computer, where it was edited using the Photoshop software. For measuring purposes, the software's measuring scale was calibrated by using the software's ruler tool to identify, as accurately as possible, the equivalent of pixel units in micrometer units. After customizing the measuring scale, a digital template was designed on a separate Photoshop layer. This digital template represented an aid-tool that facilitated the measurements at posterior mid-palatal area. Measurement locations were determined at the midline of the PPS area that coincides with the midpoint of the frontal edge of the drilled groove and at 0.5 mm equidistance on both sides of the midline. Thus, the digital template consisted of three vertical lines, one vertical



midline and the other two lines which corresponded the predetermined measurement locations (Fig. 17).

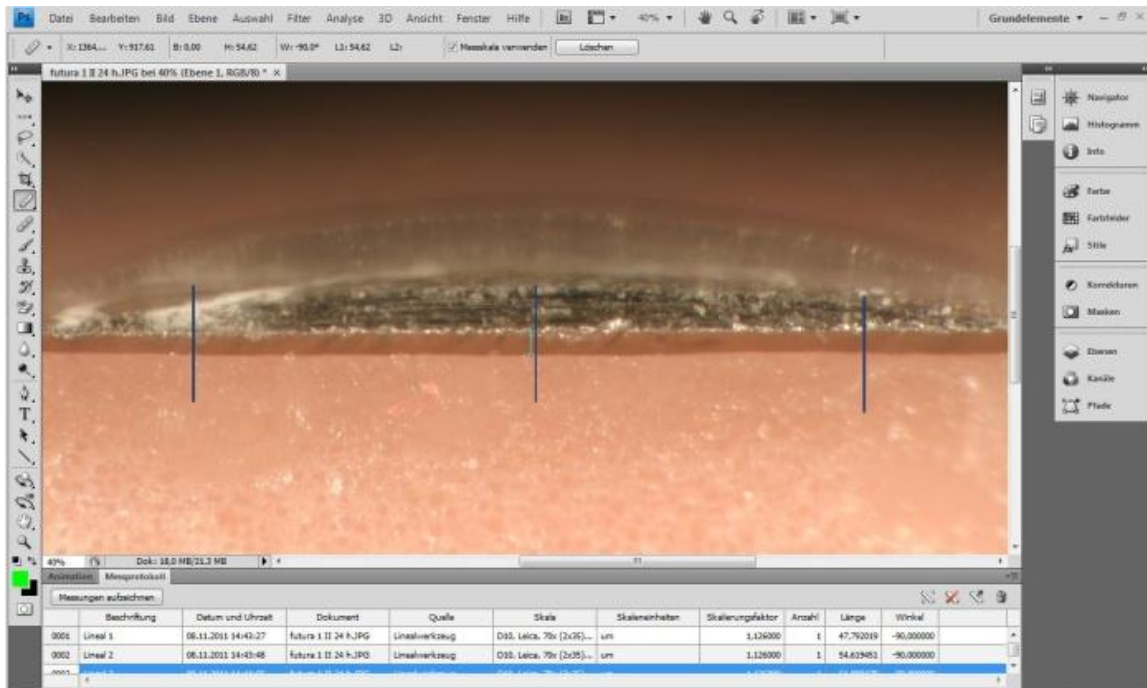


Fig. 17 – Measuring the PPS distortion of DB

### 2.2.2.4 Recording the PPS distortion

For each digital photo, the distance between each DB and the master model was measured at the three previously mentioned locations by using the formerly described calibrated software. Specimen digital image was opened in a new Photoshop layer, the digital template was overlapped over the digital image such that the digital template's midline aligned with midline of the PPS area. The digitized measurements were made parallel and directly next to the right side of the template's three vertical lines (Fig. 17).

Three measurements were recorded for each digital image, thus, six readings for each tested DB sample were obtained. Thereby, a total of 360 measurements were made for all investigated injection-molded DBs at each evaluating time interval.

## 2.3 Statistical analysis

Since the linear, volumetric, and PPS distortion measurements showed a normal distribution (Shapiro-Wilk test) but had differing variances depending upon the material, Student's or Welch's t test was utilized, as appropriate, for all comparisons of statistical significance for linear, volumetric, and PPS dimensional

changes. The significance level was set at 5% ( $\alpha = 0.05$ ) with a Bonferroni-Holm correction for multiple comparisons.

### 3 Results

The standard deviation of ten consecutive measurements of one specimen for each dimensional change variable conducted by using the digital caliper, electronic balance, and Photoshop software recorded 0.01 mm, 0.2 %, and 0.5  $\mu$ m, respectively. The linear and volumetric dimensional changes of all non anatomic-shape specimens made from the investigated DB materials, at the three time intervals of water immersion, were smaller (denoted by negative sign) than the corresponding die values. Moreover, all DB-like specimens made from the different injection-molded acrylic resin materials, at the three time intervals of water immersion displayed PPS distortion.

#### 3.1 Linear dimensional change

The linear dimensional change mean values measured at the three time intervals of water immersion and standard deviations are given in Table 2. After 30 days' storage in water all specimens had a general trend of increased linear measurements (expansion). Specimens continued to exhibit the same tendency of increased linear measurements up to 90 days of water storage (Table 2).

Statistically significant differences in linear dimensional changes between resins were found at the three time intervals of water immersion ( $p \leq 0.05$ ), with exception of the following comparisons ( $p > 0.05$ ): IvoBase Hi Impact/SR Ivocap Hi Impact and PalaXpress/Lucitone 199 after 1 day, FuturaGen/PalaXpress and PalaXpress/Lucitone 199 after 30 days and IvoBase Hybrid/IvoBase Hi Impact after 90 days (Table 2).

**Table 2 – Mean linear dimensional changes  $-\Delta L\%$ , and standard deviations ( ) of test groups measured after storage in water for 1, 30, and 90 days.**

Product	Abbreviation	1 day	30 days	90 days
IvoBase Hybrid	IBHY	-0.29 (0.01) <sup>a</sup>	-0.13 (0.02) <sup>a</sup>	-0.07 (0.02) <sup>a</sup>
IvoBase Hi Impact	IBHI	-0.35 (0.02) <sup>b</sup>	-0.19 (0.03) <sup>b</sup>	-0.09 (0.03) <sup>a</sup>
SR Ivocap Hi Impact	ICHI	-0.39 (0.05) <sup>b</sup>	-0.33 (0.05) <sup>c</sup>	-0.30 (0.05) <sup>b</sup>
FuturaGen	FUT	-1.11 (0.10) <sup>c</sup>	-0.96 (0.11) <sup>d</sup>	-0.87 (0.09) <sup>c</sup>
PalaXpress	PLX	-1.25 (0.07) <sup>d</sup>	-1.08 (0.08) <sup>de</sup>	-1.01 (0.08) <sup>d</sup>
Lucitone 199	LUC	-1.28 (0.05) <sup>d</sup>	-1.19 (0.06) <sup>e</sup>	-1.14 (0.06) <sup>e</sup>

Means with different superscript letters in each column are significantly different at the 95% confidence level.

### 3.2 Volumetric dimensional changes

The mean volumetric dimensional change values measured at the three time intervals of water immersion and standard deviations are given in Table 3. After 30 days' storage in water all specimens had a general trend of increased volumetric measurements (expansion). Specimens continued to exhibit the same tendency of increased volumetric measurements up to 90 days of water storage (Table 3).

Statistically significant differences in volumetric dimensional changes between resins were found at the three time intervals of water immersion ( $p \leq 0.05$ ) with exception of the comparison PalaXpress/FuturaGen at all three time intervals ( $p > 0.05$ ; Table 3).

**Table 3 – Mean volumetric dimensional changes  $-\Delta V\%$ , and standard deviations () of test groups measured after storage in water for 1, 30, and 90 days.**

Product	Abbreviation	1 day	30 days	90 days
IvoBase Hybrid	IBHY	-1.08 (0.09) <sup>a</sup>	-0.52 (0.08) <sup>a</sup>	-0.23 (0.09) <sup>a</sup>
IvoBase Hi Impact	IBHI	-1.39 (0.05) <sup>b</sup>	-0.92 (0.07) <sup>b</sup>	-0.56 (0.07) <sup>b</sup>
SR Ivocap Hi Impact	ICHI	-3.18 (0.15) <sup>c</sup>	-3.08 (0.16) <sup>c</sup>	-3.01 (0.15) <sup>c</sup>
PalaXpress	PLX	-4.75 (0.15) <sup>d</sup>	-4.33 (0.20) <sup>d</sup>	-4.14 (0.17) <sup>d</sup>
FuturaGen	FUT	-4.84 (0.17) <sup>d</sup>	-4.49 (0.19) <sup>d</sup>	-4.32 (0.22) <sup>d</sup>
Lucitone 199	LUC	-6.94 (0.32) <sup>e</sup>	-6.65 (0.33) <sup>e</sup>	-6.58 (0.33) <sup>e</sup>

Means with different superscript letters in each column are significantly different at the 95% confidence level.

### 3.3 PPS distortion

The PPS distortion mean values of all specimens made from the different DB materials, showed different order at each time interval of water immersion in regard to their adaptation. The mean PPS distortion values after 1 day of water immersion and standard deviations are given in Table 4.

No statistically significant differences in PPS distortions between resins were found after 1 day of water immersion ( $p > 0.05$ ), with exception of the following comparisons ( $p \leq 0.05$ ): FuturaGen/Lucitone 199, FuturaGen/SR Ivocap Hi Impact, FuturaGen/IvoBase Hi Impact and PalaXpress/IvoBase Hi Impact (Table 4).

**Table 4 – Mean PPS distortion in  $\mu\text{m}$ , and standard deviations ( ) of test groups measured after storage in water for 1 day.**

Product	Abbreviation	1 day
FuturaGen	FUT	45.17 (8.91) <sup>a</sup>
PalaXpress	PLX	49.29 (16.34) <sup>a,b</sup>
Ivobase Hybrid	IBHY	60.60 (16.89) <sup>a,b,c</sup>
Lucitone 199	LUC	65.73 (9.17) <sup>b,c</sup>
SR Ivocap Hi Impact	ICHI	72.70 (22.83) <sup>b,c</sup>
Ivobase Hi Impact	IBHI	79.55 (19.98) <sup>c</sup>

Means with different superscript letters in each column are significantly different at the 95% confidence level.

After 30 days' storage in water, HC specimens had a general trend of increased PPS distortion values. However, CC specimens had a general trend of decreased PPS distortion values (Table 5).

Statistically significant differences in PPS distortions between resins were found after 30 days of water immersion ( $p \leq 0.05$ ), with exception of the following comparisons ( $p > 0.05$ ): FuturaGen/PalaXpress, FuturaGen/IvoBase Hybrid, PalaXpress/IvoBase Hybrid, IvoBase Hybrid/IvoBase Hi Impact, IvoBase Hi Impact/Lucitone 199, IvoBase Hi Impact/SR Ivocap Hi Impact and Lucitone 199/SR Ivocap Hi Impact (Table 5).

**Table 5 – Mean PPS distortion in  $\mu\text{m}$ , and standard deviations ( ) of test groups measured after storage in water for 30 days.**

Product	Abbreviation	30 days
FuturaGen	FUT	30.58 (7.75) <sup>a</sup>
PalaXpress	PLX	31.85 (8.62) <sup>a</sup>
Ivobase Hybrid	IBHY	38.25 (12.13) <sup>a,b</sup>
IvoBase Hi Impact	IBHI	50.83 (11.00) <sup>b,c</sup>
Lucitone 199	LUC	69.27 (19.07) <sup>c</sup>
SR Ivocap Hi Impact	ICHI	79.32 (27.87) <sup>c</sup>

Means with different superscript letters in each column are significantly different at the 95% confidence level.

With the lapse of time until 90 days of water storage, HC specimens continued to exhibit the same tendency of increased PPS distortion values. Whereas, most of CC specimens had a general trend of decreased PPS values (Table 6).

Statistically significant differences in PPS distortions between resins were found after 90 days of water immersion ( $p \leq 0.05$ ), with exception of the following comparisons ( $p > 0.05$ ): PalaXpress/FuturaGen, PalaXpress/IvoBase Hybrid, FuturaGen/IvoBase Hybrid, IvoBase Hybrid/IvoBase Hi Impact and Lucitone 199/SR Ivocap Hi Impact (Table 6).

**Table 6 – Mean PPS distortion in  $\mu\text{m}$ , and standard deviations ( ) of test groups measured after storage in water for 90 days.**

Product	Abbreviation	90 days
PalaXpress	PLX	28.89 (7.69) <sup>a</sup>
FuturaGen	FUT	29.54 (7.05) <sup>a</sup>
Ivobase Hybrid	IBHY	39.36 (11.74) <sup>a,b</sup>
IvoBase Hi Impact	IBHI	45.49 (7.80) <sup>b</sup>
Lucitone 199	LUC	74.38 (23.84) <sup>c</sup>
SR Ivocap Hi Impact	ICHI	87.69 (28.34) <sup>c</sup>

Means with different superscript letters in each column are significantly different at the 95% confidence level.

## **4 Discussion**

### **4.1 Specimens design and preparation**

In the first part of the investigation, a non anatomic-shape acrylic resin specimens were fabricated. Many factors such as the shape of the palate [37, 50, 57, 59, 86, 115], the thickness of the denture [20, 50, 60, 101, 131], the presence of teeth [6, 8, 44, 127], the type of stone used for cast fabrication [116, 117], and so on, could affect the dimensional changes that might occur during processing. Therefore, using specimens with a simple shape rather than dentures or DB specimens simplified the evaluation of the linear and volumetric dimensional changes of the investigated materials, and the dimensional changes could be directly attributed to the acrylic resin and to the processing method [2, 102]. The master metal die used to produce the non anatomic-shape specimens was directly embedded in the investment gypsum. This procedure was believed to eliminate many of the variables present in attempts to produce identical wax patterns [2].

In the second part of the investigation, the master metal model used to fabricate the DB specimens was replicated by using one duplicate mold to produce one stone cast. This was thought to yield stone casts without any deformation which might arise as a result of mold distortion due to repeated usage of one mold to prepare multiple stone casts [6]. Also, dental stone mixing procedures to prepare the stone casts were accomplished by using the manufacturer's recommended water/powder ratios and spatulating under vacuum. Following manufacturer's recommendations might minimize the possible dimensional differences among the stone casts [124]. Furthermore, utilizing a duplicating mold to obtain replicas of waxed up DBs of consistent thickness was deemed essential to reproducibility of results and to minimize variation in processing dimensional changes [20, 53, 101, 115].

### **4.2 Measuring methods**

It should be clarified that the technique of using caliper has the obvious advantages of simplicity and availability [41]. However, it will be appreciated that the determination the linear dimensions using the caliper will be influenced by the force applied by the operator when using the “hand-held” caliper. This subjective-related factor can contribute to minor measurement error [33]. Furthermore, the “volume determinig technique” is sensitive to the circumferential conditions during weighing

and density determining of the specimens due to the high sensitivity of the electronic balance. These factors can contribute to minor measurement errors [98].

Also, it must be noted that the recorded PPS distortion measurements might have been influenced by placing/replacing the DBs onto the master model, since it was mentioned before that each DB was measured twice. This procedure might have probably led to negligible variation between the two measurements of the PPS distortion, which it is likely to be not significant. Additionally, the somewhat large standard deviation values of the results obtained in both two parts of the investigation resembled the standard deviation values reported by other studies concerned with evaluating dimensional changes of DB acrylic resins [57, 59, 111]. This phenomenon could not be accounted for.

### **4.3 Linear and volumetric dimensional changes**

The objective of the first part of the investigation was to assess the linear and volumetric dimensional changes of non anatomic-shape acrylic resin specimens fabricated with their specific IM technique at three time intervals of water immersion.

The investigated processed resins exhibited dimensional changes, but to a significantly and clinical relevant different extent. Therefore, the hypothesis that there is no difference in linear and volumetric dimensional changes between the various acrylic resins used with their specific IM systems has to be rejected. However, all resins were found to expand during the testing period. This increase in either linear or volumetric dimensions could be attributed to the water absorption. This was consistent with findings of earlier studies [2, 14, 77, 81, 99, 132, 135].

Volumetric dimensional changes of investigated materials after 1 day of processing ranged from -1.08% to -6.94%. In regard to the HC acrylic resins (SR Ivocap Hi Impact and Lucitone 199), the results were comparable to the findings obtained by Robison et al. [100]. Also, linear dimensional changes of IvoBase Hybrid, IvoBase Hi Impact, and SR Ivocap Hi Impact after 1 day of processing were less than 1%. These results were also in agreement with the findings reported by others [43, 102].

The linear dimensional changes of SR Ivocap Hi Impact and Lucitone 199 in our investigation were less than that reported by Anderson et al. [2]. In contrast, the linear dimensional changes of FuturaGen and PalaXpress were greater than that reported by Venus et al. [127]. The differences in reported results between our study



and these studies could be due to the use of different specimen design or measuring conditions [53].

FuturaGen and PalaXpress showed relatively high values of dimensional changes (shrinkage), in comparison to the other investigated materials with the exception of Lucitone 199, although these resin materials were already injected into the mold under a considerable pressure. An explanation for such findings can be found in the curing process [53, 61, 127], and the chemical composition of the materials [23, 53]. However, the exact constituents of the materials are not disclosed by the manufacturers [1, 82]. As well as, it might be ascribed to the processing conditions, in which the flask clamping tools (flask closure) [22, 50] do not provide a sufficient pressure applied to the flasks during processing, when compared to pressure-applying method supplied by Ivoclar Vivadent IM techniques.

FuturaGen and PalaXpress are CC acrylic resins which have slightly different powder/liquid mixing ratios, different respective processing protocols, and IM systems [127]. However, these two materials did not exhibit statistically significant differences regarding both volumetric dimensional changes at all three time intervals, and linear dimensional changes after 30 days, whereas they showed statistically significant differences in linear dimensional changes after 1 and 90 days of water immersion. Accordingly, this confirms the former findings [2, 58, 134] that the linear dimensional changes are not uniformly distributed within the processed DB resins.

IvoBase Hybrid and IvoBase Hi Impact DB resin materials exhibited the lowest values of either linear or volumetric dimensional inaccuracies in comparison to the other evaluated materials, irrespective of water immersion duration. This might be due to the chemical composition of these two materials [23, 53] or the technique-related conditions, in which the dry heat [43, 135] and pressure applied to the flask, are digitally controlled during processing procedure.

The differences shown in the post-polymerization dimensional changes between IvoBase Hybrid and IvoBase Hi Impact are interesting. The two materials are produced by the same manufacturer, and the same equipment is used for injecting the fresh resin into the flask. If one assumes the dimensional changes should be the same for the identical processing procedures, the difference, therefore, could be related to the composition of the material [23, 53], powder/liquid mixing ratio [32, 54, 72], or the polymerization protocol.

Lucitone 199 demonstrated the highest values of linear and volumetric dimensional changes in comparison to the other investigated materials. This DB material is a HC acrylic resin and has the longest curing cycle among the investigated materials. This curing cycle could induce more monomer conversion [29, 42] and, consequently, might lead to more dimensional changes. Additionally, SR Ivocap Hi Impact is also a HC acrylic resin, which is processed in boiling water for 35 minutes period. This short curing cycle could, possibly, explain the lower dimensional changes presented by SR Ivocap Hi Impact resin material in comparison to Lucitone 199. However, there are other technical variations between the latter two materials, which could contribute to the statistically different dimensional changes of them [50, 127].

#### **4.4 PPS distortion**

The objective of the second part of the evaluation was to investigate dimensional distortions in the PPS area of the studied different acrylic resin DBs at three time intervals of water immersion. Based on the obtained results the null hypothesis was rejected, since significant differences between the PPS distortions of DBs at each time interval were evident. Obviously, the order of the tested materials on the dimensional changes scale, in comparison to their order in the first study part, has dramatically altered. The partially conflicting findings of the two parts showed that these in-vitro results must be interpreted with caution.

In our investigation the results of the first part could not be clearly correlated to the results of the second part. This might be explained by the considerably different design [53, 102, 130] and thickness of the specimens [20, 50, 60, 101, 131]. A second reason might be, that the specimens in the first part were directly cured in the investment stone, whereas in the second part specimens were cured on their specific stone casts [20, 88, 115, 131].

It should be also kept in mind, that the impact of time and temperatures utilized to cure the tested materials came, evidently, into effect in the second part of this study [3, 87]. This was, namely, because of the differences in coefficients of thermal expansion between the cured materials and the dental stone [54, 66, 91]. The higher the temperature involved in curing process, the worse the distortion was, irrespective of the type of acrylic resin used e.g. FuturaGen and PalaXpress (see Table 1). Also,

the longer the time employed for curing at a definite temperature, the worse was the distortion e.g. Ivobase Hybrid and Ivobase Hi Impact (see Table 1).

Lucitone 199 and SR Ivocap Hi Impact did not exhibit statistically significant PPS distortion differences at all three time intervals which was comparable to the findings obtained by Lee and coworkers [61]. However, PPS distortion results obtained by SR Ivocap technique at the three time intervals were not in agreement with a previous findings of (Sykora & Sutow) [115], which showed that PPS distortion using the same technique was reduced by immersion in water. This could be attributed to the following variations: Inspection of PPS distortion in their study was carried out while the DBs were seating on their stone casts. Furthermore, water storage has been undertaken with 23°C water; whereas in our study this was done using 37°C distilled water, which is more clinical relevant. The water temperature might tremendously affect the velocity of water diffusion and the degree of water absorption at a definite time [14] and subsequently the stress release which might cause, consequently, a change in the shape of the DB [57, 99].

FuturaGen and PalaXpress did not exhibit statistically significant PPS distortion differences at all three time intervals which was not in agreement with the findings reported by Venus et al. [127]. Additionally, the obtained PPS distortion values in our investigation were far less. The differences in results between studies could be due to the use of different experimental conditions [53]. Venus and coworkers used a maxillary master stone model with a V-shape palate to produce polyurethane maxillary working casts, on which the DB were processed and, later on, PPS measurements were carried on the polyurethane maxillary casts. In this context, it might be noteworthy to mention that when assessing the magnitude of PPS distortion for two or more materials or techniques, the significance of the differences between materials is highly influenced by the shape/height of the palatal vault, i.e. there could be a significant difference between the investigated materials for a particular shape of the palatal vault, whereas for another different palatal vault shape there could be no significant differences between materials [115].

Braden [14] has determined the values of the equilibrium water absorption, i.e. saturation, and the water diffusion coefficient at 37°C of different types of DB acrylic resins. He found that even though HC and CC acrylic resins have comparable values of equilibrium water absorption, they revealed different values of water diffusion coefficients. In other words, when two DB materials are stored in water they will

demonstrate different amounts of absorbed water at a specified time interval of water immersion, although they would absorb the same quantities of water at saturation. Accordingly, this variation in diffusion coefficients of HC and CC resins could be a deciding factor regarding the comparisons concerning the dimensional changes of DB acrylic resins occurring during water storage period.

Therefore, until attaining the water equilibrium, compared materials would probably show different amounts of absorbed water, which in turn might result in form of various dimensional behaviors. For example, the fit of CC materials, which commonly exhibit a little thermal contraction if any [3, 130], has improved with the lapse of time from 1 day to 90 days of water storage. Whereas, the fit of HC counterparts, which usually show a higher thermal contraction has not changed, if not, has even deteriorated with the lapse of time from 1 day to 90 days of water storage. Apparently, the amount of absorbed water into HC materials succeeded in releasing the residual stress emerged during curing [57, 99] and failed to produce an appreciable expansion which could improve the fit, or it might be postulated that stress relaxation effect has overcome the expansion effect. Conversely, the enhanced fit of CC materials with the lapse of time of water storage could be probably attributed to the expansion phenomena [14, 78] or/and less amount of inherent stress relaxation [3, 69, 126].

It may seem at first glance that the profound PPS distortion of the IvoBase CC materials (IBHI, IBHY), particularly the IBHI, after 1 day of water immersion was a striking finding although these two acrylics showed the best linear and volumetric dimensional precision at the three time intervals. However, interpretation might be made as follows: Curing cycles of these CC materials include rising the temperature of the flask up to 97°C. The flask temperature is stabilized around this degree for about 20, 30 minutes for IBHY and IBHI, respectively, which means that these two acrylics receive considerable amounts of heating during polymerization. It could be assumed, thus, that the internal stresses that emerged inside the processed DBs during cooling phase have released, later, upon recovering the DBs from their specific stone casts and throughout the subsequent 24 hours of water immersion. However, the improvement in the PPS distortion of these two materials in the time period from 1 to 90 days was very remarkable, which is likely attributed to the composition of these materials [23, 53, 118] and water absorption influence [3, 66, 130].

#### **4.5 Clinical implications**

In spite of the observed dimensional changes associated with the different IM techniques and the revealed significant differences in regard to either linear and volumetric dimensional changes or the PPS distortions, it can be assumed that dentures constructed by any of these investigated materials/injection-methods would fit clinically, since it can be expected that the resilience, i.e. compressibility, of the oral mucosa within the normal physiologic limits might result in a better adaptation of the dentures [63, 97]. The magnitude of the oral mucosa compressibility could averagely range between 0.3 and 0.5 mm in the alveolar ridge region [68, 112] and might range between 0.5 and 1 mm in the PPS area [112].

Moreover, employing these materials/injection-methods in the fabrication process of implant-retained overdentures/implant-retained fixed prostheses [16, 31] could be of particular interest, since the dimensional precision is demanded in such kind of dental prostheses regarding the fit passivity of the incorporated metal framework [17, 31, 76].

## 5 Conclusions

On the basis of the results and conditions of this study, the following conclusions are drawn:

1. CC injection-molded acrylic resins exhibited, in general, more dimensional precision than HC injection-molded counterparts.
2. Linear and volumetric dimensional precision of acrylic resins polymerized by the IvoBase IM system is more accurate than that of resins processed by the other IM techniques.
3. Clinical studies should be conducted to establish a correlation with these laboratory findings.
4. Despite the statistically significant differences in dimensional precision among the tested DB materials, other aspects must be necessarily investigated in order to make the final decision about the preferable material and/or system to be used.

## 6 Summary

Dimensional precision of denture bases is a crucial factor for gaining denture retention and for attainment of clinically acceptable dentures. The dimensional precision of various denture base acrylic resins processed by the injection-molding method has not been extensively studied. Therefore, the aim of this study was to investigate the dimensional accuracy and stability of denture base materials processed by their respective injection-molding techniques by conducting and comparing the linear, volumetric, and posterior palatal seal distortion measurements over a three months observation period while the specimens are stored in 37°C temperature distilled water.

Two heat-cured (SR Ivocap Hi Impact and Lucitone 199) and four cold-cured (IvoBase Hybrid, IvoBase Hi Impact, PalaXpress, and FuturaGen) acrylic resins were used to fabricate six specimens of each material for the linear and volumetric dimensional changes evaluation, and ten specimens of each material for the posterior palatal seal distortion evaluation. Linear and volumetric dimensional changes, and posterior palatal seal distortion were determined by means of a digital caliper, an electronic hydrostatic balance, and Photoshop software, respectively, after water storage of 1, 30, and 90 days. Means and standard deviations of linear and volumetric dimensional changes were calculated in percentage (%), while means and standard deviations of posterior palatal seal distortions were calculated in micrometer ( $\mu\text{m}$ ). Statistical analysis was done using Student's and Welch's t tests with Bonferroni-Holm correction for multiple comparisons ( $\alpha=0.05$ ).

Regarding the linear and volumetric dimensional changes, statistically significant differences in linear dimensional changes between resins were demonstrated at all three time intervals of water immersion ( $p\leq 0.05$ ), with exception of the following comparisons which showed no significant difference: IvoBase Hi Impact/SR Ivocap Hi Impact and PalaXpress/Lucitone 199 after 1 day, FuturaGen/PalaXpress and PalaXpress/Lucitone 199 after 30 days, and IvoBase Hybrid/IvoBase Hi Impact after 90 days. Also, statistically significant differences in volumetric dimensional changes between resins were found at all three time intervals of water immersion ( $p\leq 0.05$ ), with exception of the comparison between PalaXpress and FuturaGen.

Regarding the posterior palatal seal distortion, no statistically significant differences between resins were found after 1 day of water immersion ( $p > 0.05$ ), with exception of the following comparisons ( $p \leq 0.05$ ): FuturaGen/Lucitone 199, FuturaGen/SR Ivocap Hi Impact, FuturaGen/IvoBase Hi Impact and PalaXpress/IvoBase Hi Impact. After 30 days of water immersion, statistically significant differences between resins were found ( $p \leq 0.05$ ), with exception of the following comparisons ( $p > 0.05$ ): FuturaGen/PalaXpress, FuturaGen/IvoBase Hybrid, PalaXpress/IvoBase Hybrid, IvoBase Hybrid/IvoBase Hi Impact, IvoBase Hi Impact/Lucitone 199, IvoBase Hi Impact/SR Ivocap Hi Impact and Lucitone 199/SR Ivocap Hi Impact. After 90 days of water immersion, statistically significant differences between resins were found ( $p \leq 0.05$ ), with exception of the following comparisons ( $p > 0.05$ ): PalaXpress/FuturaGen, PalaXpress/IvoBase Hybrid, FuturaGen/IvoBase Hybrid, IvoBase Hybrid/IvoBase Hi Impact and Lucitone 199/SR Ivocap Hi Impact.

Under the conditions of this study, cold-cured injection-molded acrylic resins exhibited more dimensional precision than heat-cured injection-molded counterparts, and the cold-cured IvoBase materials, processed by the new injection-molding system (IvoBase), revealed superior linear and volumetric dimensional precision.



## 7 Zusammenfassung

Die Präzision der Dimensionen von Prothesenbasen ist ein entscheidender Faktor für die Gewinnung des Prothesenhaltes und zur Erreichung klinisch akzeptabler Prothesen. Die Präzision der Dimensionen der verschiedenen Prothesenbasenwerkstoffe, hergestellt im Spritzgussverfahren, wurde bisher nicht umfassend untersucht. Das Ziel dieser Studie war es, die Dimensionsgenauigkeit und -stabilität der Prothesenbasenwerkstoffe, die durch ihre zugehörigen Spritzgussverfahren verarbeitet wurden, zu untersuchen. Linear-, Volumen-, sowie Verzerrungsvermessungen der dorsalen Randspalten wurden über einen Beobachtungszeitraum von drei Monaten durchgeführt und verglichen. Während dieser Zeit wurden die Proben in 37°C destilliertem Wasser gelagert.

Zwei Heißpolymerisate (SR Ivocap Hi Impact und Lucitone 199) und vier Kaltpolymerisate (IvoBase Hybrid, IvoBase Hi Impact, PalaXpress und FuturaGen) zur Herstellung von Prothesenbasen wurden verwendet. Aus diesen Materialien wurden je sechs Proben zur Auswertung der linearen und volumetrischen Dimensionsänderungen und je zehn Proben zur Auswertung der Verzerrungsvermessungen der dorsalen Randspalten hergestellt. Lineare und volumetrische Dimensionsänderungen sowie Verzerrung der dorsalen Randspalten wurden mittels einer digitalen Schiebelehre, einer elektronischen hydrostatischen Waage und Photoshop-Software jeweils nach Wasserlagerung von 1, 30 und 90 Tagen bestimmt. Die Mittelwerte und Standardabweichungen der linearen- und volumetrischen Dimensionsänderungen wurden in Prozent (%) berechnet, wohingegen die Mittelwerte und Standardabweichungen der Verzerrung der dorsalen Randspalten in  $\mu\text{m}$  berechnet wurden. Die statistische Analyse wurde mit dem Student und Welch t-Tests, korrigiert nach Bonferroni-Holm für Mehrfachvergleiche ( $\alpha = 0,05$ ), durchgeführt.

Bezüglich der linearen und volumetrischen Dimensionsänderungen wurden statistisch signifikante Unterschiede in der linearen Dimensionsänderungen zwischen den Kunststoffmaterialien bei allen drei Zeitintervallen der Wasserlagerung nachgewiesen ( $p \leq 0,05$ ), mit Ausnahme der folgenden Vergleiche, die keine signifikanten Unterschiede zeigten: IvoBase Hi Impact/SR Ivocap Hi Impact und PalaXpress/Lucitone 199 nach 1 Tag, FuturaGen/PalaXpress und PalaXpress/Lucitone 199 nach 30 Tagen, und IvoBase Hybrid/IvoBase Hi Impact nach 90 Tagen. Zusätzlich wurden statistisch signifikante Unterschiede in den

volumetrischen Dimensionsänderungen zwischen den Kunststoffmaterialien bei allen drei Zeitintervallen der Wasserlagerung nachgewiesen ( $p \leq 0,05$ ), mit Ausnahme des Vergleichs zwischen PalaXpress und FuturaGen.

Bezüglich der Verzerrung der dorsalen Randspalten, wiesen die untersuchten Materialien keine statistisch signifikanten Unterschiede nach 1 Tag Wasserlagerung auf ( $p > 0,05$ ), mit Ausnahme der folgenden Vergleiche ( $p \leq 0,05$ ): FuturaGen/Lucitone 199, FuturaGen/SR Ivocap Hi Impact, FuturaGen/IvoBase Hi Impact und PalaXpress/IvoBase Hi Impact. Nach 30 Tagen Wasserlagerung wurden statistisch signifikante Unterschiede zwischen den Kunststoffmaterialien nachgewiesen ( $p \leq 0,05$ ), mit Ausnahme der folgenden Vergleiche ( $p > 0,05$ ): FuturaGen/PalaXpress, FuturaGen/IvoBase Hybrid, PalaXpress/IvoBase Hybrid, IvoBase Hybrid/IvoBase Hi Impact, IvoBase Hi Impact/Lucitone 199, IvoBase Hi Impact/SR Ivocap Hi Impact und Lucitone 199/SR Ivocap Hi Impact. Nach 90 Tagen Wasserlagerung waren statistisch signifikante Unterschiede zwischen fast allen Kunststoffmaterialien nachweisbar ( $p \leq 0,05$ ), mit Ausnahme der folgenden Vergleiche ( $p > 0,05$ ): PalaXpress/FuturaGen, PalaXpress/IvoBase Hybrid, FuturaGen/IvoBase Hybrid, IvoBase Hybrid/IvoBase Hi Impact und Lucitone 199/SR Ivocap Hi Impact.

Unter den Bedingungen dieser Studie zeigten Kaltpolymerisate in der Injektions-Technik eine größere Präzision der Dimensionen als Heißpolymerisate. Das Kaltpolymerisat IvoBase, das durch ein neues Spritzguss-System (IvoBase) verarbeitet wurde, zeigte überlegenere lineare und volumetrische Präzision der Dimensionen.

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**10 Dedication**

Finally, I dedicate this thesis to:

My parents .....Ahmad Mohsin and Eva

My wife .....Shurouk

My children .....Fadi and Rami

My sister .....Lana

Thank you all for your comprehension, love, and encouragement.

## 11 Curriculum Vitae

### Persönliche Daten

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### Studium

1992-1997 Studium der Zahnmedizin an der Fakultät für Zahnmedizin der Universität Damaskus.

1997-1999 Diplom des postgradualen Studiums im Bereich der festsitzenden Prothetik an der Fakultät für Zahnmedizin der Universität Damaskus.

2001-2003 Diplom des postgradualen Studiums im Bereich der herausnehmbaren Prothetik an der Fakultät für Zahnmedizin der Universität Damaskus.

2008 Erwerb des Grades Magister auf dem Gebiet "Zahnärztliche Prothetik" an der Fakultät für Zahnmedizin der Universität Damaskus.

### Berufstätigkeit

1997-2001 Assistenz Zahnarzt an der Abteilung "Kronen und Brücken" der Fakultät für Zahnmedizin der Universität Damaskus.

2001-2010 Assistenz Zahnarzt an der Abteilung



"Herausnehmbare Prothesen" der Fakultät für Zahnmedizin der Universität Damaskus.

2000-2010	Zahnärztliche Berufsausübung in Bereiche der Endodontologie, Restaurative Zahnheilkunde, Kinder- und Jugendzahnheilkunde, dentoalveoläre Chirurgie und Prothetik in eigener Praxis.
2010- Jetzt	Gastwissenschaftlicher Zahnarzt an der Klinik für zahnärztliche Prothetik des Universitätsklinikums Kiel.

### Wissenschaftliche Publikationen

- Dimensional changes of injection-molded PMMA denture base resins. S. El Bahra, K. Ludwig, M. Kern. J Dent Res 2013; 92, Spec Iss A, Abstr No 2444.
- Linear and volumetric dimensional changes of injection-molded PMMA denture base resins. S. El Bahra, K. Ludwig, A. Samran, S. Freitag-Wolf, M. Kern. Dent Mater 2013; 29:1091-1097.

### Sprachkenntnisse

- Arabisch: Sehr Gut
- Deutsch, Englisch: Gut
- Tschechisch: Befriedigend

### Hobbies

- Lesen
- Schwimmen

## 12 Appendix

**Table 7 – Linear dimensional changes  $-\Delta L\%$  of test group (ICHI) measured after storage in water for 1, 30, and 90 days.**

	1 day	30 days	90 days
Specimen 1	- 0.33	- 0.25	- 0.22
Specimen 2	- 0.45	- 0.38	- 0.36
Specimen 3	- 0.45	- 0.38	- 0.36
Specimen 4	- 0.36	- 0.29	- 0.27
Specimen 5	- 0.36	- 0.31	- 0.29
Specimen 6	- 0.40	- 0.36	- 0.33
Mean	- 0.39	- 0.33	- 0.30
S.D.	$\pm 0.05$	$\pm 0.05$	$\pm 0.05$

**Table 8 – Linear dimensional changes  $-\Delta L\%$  of test group (PLX) measured after storage in water for 1, 30, and 90 days.**

	1 day	30 days	90 days
Specimen 1	- 1.14	- 0.96	- 0.89
Specimen 2	- 1.31	- 1.16	- 1.09
Specimen 3	- 1.31	- 1.16	- 1.07
Specimen 4	- 1.25	- 1.07	- 1.00
Specimen 5	- 1.27	- 1.14	- 1.07
Specimen 6	- 1.23	- 1.02	- 0.94
Mean	- 1.25	- 1.08	- 1.01
S.D.	$\pm 0.07$	$\pm 0.08$	$\pm 0.08$

**Table 9 – Linear dimensional changes  $-\Delta L\%$  of test group (LUC) measured after storage in water for 1, 30, and 90 days.**

	1 day	30 days	90 days
Specimen 1	- 1.36	- 1.27	- 1.23
Specimen 2	- 1.31	- 1.25	- 1.18
Specimen 3	- 1.27	- 1.18	- 1.14
Specimen 4	- 1.20	- 1.09	- 1.05
Specimen 5	- 1.27	- 1.16	- 1.09
Specimen 6	- 1.27	- 1.20	- 1.14
Mean	- 1.28	- 1.19	- 1.14
S.D.	$\pm 0.05$	$\pm 0.06$	$\pm 0.06$

**Table 10 – Linear dimensional changes  $-\Delta L\%$  of test group (FUT) measured after storage in water for 1, 30, and 90 days.**

	1 day	30 days	90 days
Specimen 1	- 1.07	- 0.94	- 0.85
Specimen 2	- 1.00	- 0.85	- 0.76
Specimen 3	- 1.00	- 0.85	- 0.78
Specimen 4	- 1.14	- 0.98	- 0.91
Specimen 5	- 1.20	- 1.07	- 0.96
Specimen 6	- 1.23	- 1.09	- 0.98
Mean	- 1.11	- 0.96	- 0.87
S.D.	$\pm 0.10$	$\pm 0.11$	$\pm 0.09$

**Table 11 – Linear dimensional changes  $-\Delta L\%$  of test group (IBHI) measured after storage in water for 1, 30, and 90 days.**

	1 day	30 days	90 days
Specimen 1	- 0.36	- 0.20	- 0.09
Specimen 2	- 0.36	- 0.20	- 0.11
Specimen 3	- 0.38	- 0.25	- 0.13
Specimen 4	- 0.33	- 0.18	- 0.07
Specimen 5	- 0.33	- 0.16	- 0.04
Specimen 6	- 0.33	- 0.16	- 0.07
Mean	- 0.35	- 0.19	- 0.09
S.D.	$\pm 0.02$	$\pm 0.03$	$\pm 0.03$

**Table 12 – Linear dimensional changes  $-\Delta L\%$  of test group (IBHY) measured after storage in water for 1, 30, and 90 days.**

	1 day	30 days	90 days
Specimen 1	- 0.29	- 0.13	- 0.07
Specimen 2	- 0.29	- 0.11	- 0.04
Specimen 3	- 0.27	- 0.11	- 0.04
Specimen 4	- 0.29	- 0.11	- 0.07
Specimen 5	- 0.29	- 0.13	- 0.07
Specimen 6	- 0.31	- 0.16	- 0.11
Mean	- 0.29	- 0.13	- 0.07
S.D.	$\pm 0.01$	$\pm 0.02$	$\pm 0.02$

**Table 13 – Volumetric dimensional changes  $-\Delta V\%$  of test group (ICHI) measured after storage in water for 1, 30, and 90 days.**

	1 day	30 days	90 days
Specimen 1	- 3.28	- 3.18	- 3.16
Specimen 2	- 2.99	- 2.88	- 2.82
Specimen 3	- 3.22	- 3.09	- 3.05
Specimen 4	- 3.02	- 2.94	- 2.86
Specimen 5	- 3.39	- 3.31	- 3.18
Specimen 6	- 3.15	- 3.07	- 2.98
Mean	- 3.18	- 3.08	- 3.01
S.D.	$\pm 0.15$	$\pm 0.16$	$\pm 0.15$

**Table 14 – Volumetric dimensional changes  $-\Delta V\%$  of test group (PLX) measured after storage in water for 1, 30, and 90 days.**

	1 day	30 days	90 days
Specimen 1	- 4.64	- 4.15	- 3.98
Specimen 2	- 4.51	- 4.05	- 3.88
Specimen 3	- 4.86	- 4.36	- 4.22
Specimen 4	- 4.80	- 4.44	- 4.23
Specimen 5	- 4.77	- 4.44	- 4.23
Specimen 6	- 4.91	- 4.57	- 4.32
Mean	- 4.75	- 4.33	- 4.14
S.D.	$\pm 0.15$	$\pm 0.20$	$\pm 0.17$

**Table 15 – Volumetric dimensional changes  $-\Delta V\%$  of test group (LUC) measured after storage in water for 1, 30, and 90 days.**

	1 day	30 days	90 days
Specimen 1	- 7.03	- 6.77	- 6.65
Specimen 2	- 6.78	- 6.50	- 6.43
Specimen 3	- 7.46	- 7.18	- 7.14
Specimen 4	- 6.52	- 6.22	- 6.17
Specimen 5	- 7.05	- 6.74	- 6.71
Specimen 6	- 6.80	- 6.50	- 6.40
Mean	- 6.94	- 6.65	- 6.58
S.D.	$\pm 0.32$	$\pm 0.33$	$\pm 0.33$

**Table 16 – Volumetric dimensional changes  $-\Delta V\%$  of test group (FUT) measured after storage in water for 1, 30, and 90 days.**

	1 day	30 days	90 days
Specimen 1	- 4.99	- 4.68	- 4.49
Specimen 2	- 4.89	- 4.56	- 4.41
Specimen 3	- 5.07	- 4.74	- 4.61
Specimen 4	- 4.65	- 4.28	- 4.10
Specimen 5	- 4.75	- 4.40	- 4.22
Specimen 6	- 4.68	- 4.30	- 4.08
Mean	- 4.84	- 4.49	- 4.32
S.D.	$\pm 0.17$	$\pm 0.19$	$\pm 0.22$

**Table 17 – Volumetric dimensional changes  $-\Delta V\%$  of test group (IBHI) measured after storage in water for 1, 30, and 90 days.**

	1 day	30 days	90 days
Specimen 1	- 1.48	- 0.99	- 0.65
Specimen 2	- 1.39	- 0.96	- 0.59
Specimen 3	- 1.39	- 0.93	- 0.56
Specimen 4	- 1.39	- 0.96	- 0.59
Specimen 5	- 1.33	- 0.80	- 0.46
Specimen 6	- 1.36	- 0.88	- 0.52
Mean	- 1.39	- 0.92	- 0.56
S.D.	$\pm 0.05$	$\pm 0.07$	$\pm 0.07$

**Table 18 – Volumetric dimensional changes  $-\Delta V\%$  of test group (IBHY) measured after storage in water for 1, 30, and 90 days.**

	1 day	30 days	90 days
Specimen 1	- 1.13	- 0.57	- 0.26
Specimen 2	- 1.00	- 0.44	- 0.13
Specimen 3	- 1.05	- 0.48	- 0.17
Specimen 4	- 0.99	- 0.44	- 0.14
Specimen 5	- 1.22	- 0.66	- 0.37
Specimen 6	- 1.11	- 0.55	- 0.29
Mean	- 1.08	- 0.52	- 0.23
S.D.	$\pm 0.09$	$\pm 0.08$	$\pm 0.09$

**Table 19 – PPS distortion in  $\mu\text{m}$  of test group (ICHI) measured after storage in water for 1, 30, and 90 days.**

	1 day	30 days	90 days
Specimen 1	63.94	70.75	79.89
Specimen 2	77.56	82.30	99.17
Specimen 3	88.81	96.21	116.64
Specimen 4	29.60	30.79	39.96
Specimen 5	86.44	106.28	113.35
Specimen 6	85.55	90.29	90.27
Specimen 7	102.97	120.33	107.41
Specimen 8	39.37	37.60	39.37
Specimen 9	70.75	78.74	109.78
Specimen 10	82.00	79.93	81.09
Mean	72.70	79.32	87.69
S.D.	$\pm 22.83$	$\pm 27.87$	$\pm 28.34$

**Table 20 – PPS distortion in  $\mu\text{m}$  of test group (PLX) measured after storage in water for 1, 30, and 90 days.**

	1 day	30 days	90 days
Specimen 1	61.57	32.86	25.75
Specimen 2	34.64	30.49	30.79
Specimen 3	54.62	39.08	38.48
Specimen 4	36.26	25.46	25.16
Specimen 5	50.77	31.38	30.20
Specimen 6	42.04	30.79	31.67
Specimen 7	46.77	22.50	16.28
Specimen 8	26.49	19.24	18.35
Specimen 9	55.51	37.89	32.25
Specimen 10	84.22	48.85	39.96
Mean	49.29	31.85	28.89
S.D.	$\pm 16.34$	$\pm 8.62$	$\pm 7.69$

**Table 21 – PPS distortion in  $\mu\text{m}$  of test group (LUC) measured after storage in water for 1, 30, and 90 days.**

	1 day	30 days	90 days
Specimen 1	82.00	98.13	123.68
Specimen 2	65.13	91.47	100.60
Specimen 3	61.57	87.92	84.94
Specimen 4	74.45	61.72	66.61
Specimen 5	69.86	63.80	59.80
Specimen 6	70.46	70.90	72.81
Specimen 7	61.72	65.28	68.09
Specimen 8	50.92	33.30	37.00
Specimen 9	54.62	56.10	65.70
Specimen 10	66.61	64.09	64.54
Mean	65.73	69.27	74.38
S.D.	$\pm 9.17$	$\pm 19.07$	$\pm 23.84$

**Table 22 – PPS distortion in  $\mu\text{m}$  of test group (FUT) measured after storage in water for 1, 30, and 90 days.**

	1 day	30 days	90 days
Specimen 1	56.54	40.41	36.10
Specimen 2	36.41	25.90	27.82
Specimen 3	45.00	28.27	21.61
Specimen 4	43.96	26.50	24.27
Specimen 5	39.96	18.95	16.87
Specimen 6	49.59	41.59	37.00
Specimen 7	60.54	39.22	37.59
Specimen 8	47.07	34.04	33.44
Specimen 9	30.71	23.98	27.82
Specimen 10	41.89	26.94	32.86
Mean	45.17	30.58	29.54
S.D.	$\pm 8.91$	$\pm 7.75$	$\pm 7.05$

**Table 23 – PPS distortion in  $\mu\text{m}$  of test group (IBHI) measured after storage in water for 1, 30, and 90 days.**

	1 day	30 days	90 days
Specimen 1	81.41	58.17	48.83
Specimen 2	48.11	41.30	39.95
Specimen 3	67.35	51.21	52.67
Specimen 4	56.69	25.90	30.77
Specimen 5	110.57	48.99	49.12
Specimen 6	87.92	56.10	39.95
Specimen 7	94.14	64.68	56.84
Specimen 8	67.35	47.96	39.07
Specimen 9	102.72	59.80	48.24
Specimen 10	79.19	54.17	49.44
Mean	79.55	50.83	45.49
S.D.	$\pm 19.98$	$\pm 11.00$	$\pm 7.80$

**Table 24 – PPS distortion in  $\mu\text{m}$  of test group (IBHY) measured after storage in water for 1, 30, and 90 days.**

	1 day	30 days	90 days
Specimen 1	63.94	37.45	37.59
Specimen 2	101.24	70.46	64.21
Specimen 3	57.13	33.45	26.05
Specimen 4	46.77	26.64	29.90
Specimen 5	48.70	35.38	38.77
Specimen 6	44.55	34.34	40.54
Specimen 7	74.16	43.07	55.35
Specimen 8	53.29	30.34	32.85
Specimen 9	52.99	33.90	34.33
Specimen 10	63.20	37.45	34.04
Mean	60.60	38.25	39.36
S.D.	$\pm 16.89$	$\pm 12.13$	$\pm 11.74$