# **Evaluation of Mechanical and Thermal Properties of Commonly Used Denture Base Resins**

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<u>Purpose</u>: The purpose of this investigation was to evaluate and compare the mechanical and thermal properties of 6 commonly used polymethyl methacrylate denture base resins.

<u>Materials and Methods</u>: Sorption, solubility, color stability, adaptation, flexural stiffness, and hardness were assessed to determine compliance with ADA Specification No. 12. Thermal assessments were performed using differential scanning calorimetry and dynamic mechanical analysis. Results were assessed using statistical and observational analyses.

<u>Results</u>: All materials satisfied ADA requirements for sorption, solubility, and color stability. Adaptation testing indicated that microwave-activated systems provided better adaptation to associated casts than conventional heat-activated resins. According to flexural testing results, microwaveable resins were relatively stiff, while rubber-modified resins were more flexible. Differential scanning calorimetry indicated that microwave-activated systems were more completely polymerized than conventional heat-activated materials.

<u>Conclusion</u>: The microwaveable resins displayed better adaptation, greater stiffness, and greater surface hardness than other denture base resins included in this investigation. Elastomeric toughening agents yielded decreased stiffness, decreased surface hardness, and decreased glass transition temperatures.

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INDEX WORDS: PMMA, adaptation, thermal analysis, differential scanning calorimetry, dynamic mechanical analysis

**P**OLYMETHYL METHACRYLATE (PMMA) resins have dominated the denture base market for more than 50 years. This dominance has been supported by physical and esthetic properties of PMMA, as well as the material's availability, reasonable cost, and ease of manipulation.<sup>1-5</sup>

For several years, PMMA resins were molded using simple compression techniques. Polymerization was accomplished by heating the molded ma-

Accepted May 21, 2003

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Copyright © 2004 by The American College of Prosthodontists 1059-941X/04 doi: 10.1111/j.1532-849X.2004.04002.x terials in water baths. With advances in polymer science, new molding and activation techniques were introduced.<sup>6-9</sup> Improved polymers were also developed.<sup>10,11</sup> These advances led to the introduction of injection-molding techniques, microwave activation, and polymers exhibiting improved impact resistance.

Testing procedures for PMMA denture base resins are prescribed in ADA Specification No. 12. This specification permits the use of uncomplicated instrumentation and techniques to assess material properties. As might be expected, a number of more complex tests also may be used to characterize the behavior of dental polymers. Among the most useful tests are those that characterize the physical properties of polymers as a function of temperature. While the results of such tests have been presented in the dental literature for more than 30 years,<sup>12-20</sup> these evaluations are relatively rare and warrant particular attention. Therefore, a brief explanation of applied thermal techniques is provided.

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# **Thermal Analysis**

Thermal analysis may be described as a family of techniques for determining the physical properties of polymers through a defined range of temperatures. Thermal techniques display several common characteristics, including the use of relatively small specimens, precise temperature control, and rapid characterization. Among the most commonly used thermal techniques are differential scanning calorimetry and dynamic mechanical analysis.

Differential scanning calorimetry and dynamic mechanical analysis permit the identification of important physical properties. Polymeric materials such as polymethyl methacrylate exhibit important changes in mechanical behavior as material temperature is altered. One of the most useful descriptors of a polymeric material's state is the glass transition temperature  $(T_g)$ . This is the temperature at which larger polymer chains are able to move rather freely within the polymeric mass. This results in a material that transforms from a brittle solid below Tg to a rubbery solid above T<sub>g</sub>. The glass transition temperature is affected by many factors, including the degree of polymerization, presence of plasticizers, and the moisture content of the material. Generally, an increased degree of polymerization yields an increased Tg, whereas the presence of plasticizers yields a decreased T<sub>g</sub>.

Both differential scanning calorimetry and dynamic mechanical analysis may be used to identify  $T_g$ , as well as other important physical and chemical characteristics. As a result, the equipment and techniques used in differential scanning calorimetry and dynamic mechanical analysis testing are described in the following sections.

## **Differential Scanning Calorimetry**

A differential scanning calorimeter consists of an experimental chamber and a computer (Fig 1). Within the experimental chamber are two pans. Each pan is connected to its own heater. The pans and heaters are connected to a computer that monitors the temperature of each pan and controls each heater.

During differential scanning calorimetry testing, a polymer sample is placed into one pan. The remaining pan serves as a reference. A desired heating rate is entered into the computer, and the

# DSC testing apparatus



Figure 1. Differential scanning calorimeter.

system is activated. The computer monitors the system to ensure consistent, simultaneous heating of both pans.

As might be expected, the polymer acts as a "heat sink." Therefore, if the temperatures of the two pans are to be elevated at the same rate, more heat must be applied to the pan containing the polymer. By monitoring and recording the heat flow to each pan, the computer also tracks the heat differential between specimen and reference pans. This heat differential represents heat flow to the polymeric specimen. In turn, this heat flow is plotted against temperature (Fig 2). The resultant plot provides a continuous description of the polymer's variation in heat capacity with temperature.

On a standard differential scanning calorimetry plot, heat flow into the specimen is negative while heat flow out of the specimen is positive. Therefore, endothermic processes appear as "valleys," whereas exothermic processes produce



**Figure 2.** Representation of a DSC tracing. (This tracing was not made from a test specimen.)

"peaks." Careful examination of a differential scanning calorimetry plot permits an investigator to identify the glass transition temperature, assess residual reactivity, and characterize crystallization and melting behavior of a polymeric specimen.

On a differential scanning calorimetry trace, the glass transition temperature ( $T_g$ ) appears as a downward step in the heat flow (Fig 2). In contrast, residual polymerization is an exothermic reaction that appears as a peak on the differential scanning calorimetry trace. This peak generally occurs at a temperature above the  $T_g$ , and can be integrated to determine the heat released by completion of the polymerization process. This permits the investigator to assess the completeness of polymerization and unreacted monomer content within a polymeric specimen. This technique has been successfully employed in previous dental investigations by McCabe and Wilson,<sup>16</sup> and by Oyama and Imai.<sup>17</sup>

## **Dynamic Mechanical Analysis**

A representative dynamic mechanical analysis instrument consists of a temperature-controlled mechanical testing chamber and a computer (Fig 3). The testing chamber consists of a furnace, a specimen holder, a motor-driven mechanical testing apparatus, and a displacement measuring system. The computer is responsible for controlling experimental parameters and recording results.

For testing purposes, a specimen is placed into the specimen holder. The specimen is then subjected to a cyclic load or displacement of the desired frequency or amplitude. During this process,

## DMA testing apparatus



Figure 3. Dynamic mechanical analyzer.



Figure 4. Representative DMA trace.

the temperature within the testing chamber is elevated according to a predetermined schedule. Material response is continuously measured, and material constants are determined as a function of temperature.

In a cyclic strain experiment with a polymeric material, the dynamic mechanical analysis instrument measures the load response of the specimen and calculates components of the material response (modulus). Measurements are plotted as elastic energy storage, or "storage modulus," and viscous energy dissipation, or "loss modulus" (Fig 4). Since denture base polymers display viscous and elastic properties, both moduli are necessary to completely describe deformation response. The glass transition temperature  $(T_g)$  can be estimated from graphic representations of either modulus. On the storage modulus plot, Tg appears as a sharp drop. Conversely, Tg appears as a peak on the loss modulus curve. Dental applications of dynamic mechanical analysis testing have been validated by Clarke,<sup>18-20</sup> and by Tamereselvy and Rueggeberg.<sup>21</sup>

The purpose of this investigation was to evaluate and compare commonly used denture base resins with regard to mechanical and thermal properties. Adaptation of resin specimens to associated casts also was assessed.

## **Materials and Methods**

Six commonly used denture resin systems were included in this investigation (Table 1). Manufacturers' recommendations were used in fabrication and recovery of all specimens. Established testing protocols were employed when available, and are identified in the following sections. All instruments and devices used

Material	Fabrication Process	Manufacturer
Acron MC	Compression molding Microwave activation	GC Lab Technologies, Inc. Lockport, IL
Acron MC	Injection molding Microwave activation	GC Lab Technologies, Inc. Lockport, IL
Lucitone CH	Compression molding Water bath activation	Dentsply International York, PA
Lucitone 199 (rubber-modified resin)	Compression molding Water bath activation	Dentsply International York, PA
Lucitone 199 (rubber-modified resin)	Injection molding Water bath activation	Dentsply International York, PA
SR Ivocap	Injection molding Water bath activation	Ivoclar AG Schaan, Leichtenstein

Table 1. Materials, Fabrication Processes, and Manufacturers

in this investigation were calibrated and monitored in accordance with manufacturers' recommendations.

# Sorption, Solubility, and Color Stability Testing

In compliance with ADA Specification No. 12, two specimens of each denture base material were fabricated for sorption, solubility, and color stability testing. Individual specimens were 50 mm in diameter and 0.5 mm in thickness. Standard tests of sorption, solubility, and color stability were performed in accordance with ADA Specification No. 12.

Sorption testing was accomplished by creating two disks using each material. Disks were  $50 \pm 1$  mm in diameter and  $0.8 \pm 0.1$  mm thick. Subsequently, the thickness of each disk was reduced to  $0.5 \pm 0.05$  mm using abrasive papers in successive grits of 120, 240, 400, and 600. Grinding was performed to ensure that the surfaces of these disks were flat and parallel. Abrasive papers were flooded with water throughout the grinding procedures.

Upon completion of grinding procedures, disks were dried in a desiccator containing anhydrous calcium sulfate at  $37 \pm 2^{\circ}$ C for 24 hours. Individual disks were then placed in a similar desiccator at room temperature for 1 hour, and subsequently weighed with a precision of 0.2 mg. This cycle was repeated until the weight loss of each disk was not more than 0.5 mg in any 24-hour period.

Disks were immersed in distilled water at  $37 \pm 1^{\circ}$ C for 7 days. At the end of this period, individual disks were removed from the water with forceps, wiped with a clean dry towel, permitted to air dry for 15 seconds, and weighed. Water sorption for each disk was calculated using the formula:

Sorption  $(mg/cm^2)$ 

= [mass after immersion (mg)

- dry mass (mg)] surface area (cm<sup>2</sup>)

The average value for each material was recorded to the nearest 0.01 mg/cm<sup>2</sup>. In turn, these disks were used to determine solubility values. The disks were reconditioned to constant weight using the desiccation techniques previously described. Solubility for each disk was determined using the formula:

Solubility (mg/cm<sup>2</sup>) = [dry mass (mg) - reconditioned mass (mg)] × surface area (cm<sup>2</sup>)

The average value for each material was recorded to the nearest  $0.01 \text{ mg/cm}^2$ . These disks were then subjected to color stability testing. To accomplish this, individual disks were clearly identified and then cut in half. One half of each disk was stored. The remaining half of each disk was placed on an aluminum turntable rotating at 33 rpm, and exposed to the radiation of an S-1 bulb rated at 400 W, for 24 hours. The distance from the turntable to the bulb was held constant at 17.8 mm, and each specimen was located 127 mm from the center of the turntable. The temperature was maintained at 60–65°C throughout the exposure. Upon completion of the prescribed exposure, the exposed portion of each disk was compared with the unexposed portion to determine whether a perceptible color change had occurred.

Results were compared to established performance requirements.

## **Flexural Testing**

Twelve specimens for each material were prepared for flexural testing. Six specimens of each material were subjected to the flexural testing protocol in ADA Specification No. 12, while the remaining 6 specimens were subjected to flexural tests described in ISO 1657. Individual specimens were machined to 65 mm × 10 mm × 2.5 mm using a rotary grinding table (LECO Corp., St. Joseph, MI) in conjunction with 200, 400, 600, and 800 grit abrasive wheels. Following completion of the machining process, the specimens were stored in a water bath at  $37 \pm 2^{\circ}$ C for 50 hours. Individual specimens were then removed from the water bath, dried, and immediately tested.

As per ADA Specification No. 12, specimens were positioned in a three-point bending apparatus and subjected to progressive loading from 1500 g (14.71 N) to 5000 g (49.03 N). Transverse deflection of individual specimens was monitored and recorded. Results were compared to established performance requirements set forth in the ADA specification.

In compliance with ISO 1657, 6 specimens from each resin system also were subjected to flexural testing using a Sintech 65G test frame controlled by Testworks software (MTS Systems Corp., Eden Prairie, MN). Individual specimens were tested in a three-point bending configuration. A crosshead rate of 5 mm/min was used. Measurement and data reduction followed American Society for Testing and Materials (ASTM) standard D790. A flexural modulus was determined for each material. Results were analyzed using ANOVA and Fisher's least significant difference tests.

## Hardness Testing

Because of specimen rebound, hardness is usually not reported when mechanical properties of resins are tested. A sample size of 3 was selected and tests were performed to provide a general measure of brittleness. Hardness testing so performed is included in this document as a general reference to the reader.

Using a protocol accepted under ADA Specification No. 12, samples of each resin were machined to  $65 \text{ mm} \times 10 \text{ mm} \times 2.5 \text{ mm}$  using the equipment and materials previously described for flexural testing specimens. Specimens were stored in water for 50 hours prior to testing. Immediately prior to testing, individual specimens were removed from the water bath and dried using a clean laboratory tissue (Kimwipes EX-L, Kimberly-Clark, Roswell, GA).

The hardness of each material was evaluated using a Shore D Durometer (Instron Corp., Canton, MA). The durometer reading was recorded 1 second after indenter application. Results were compared using ANOVA and Fisher's least significant difference analyses.

## **Differential Scanning Calorimetry**

Specimens for differential scanning calorimetry were 25 mg chips of material harvested from machined blocks of each resin tested. Chips were dried in a desiccator containing anhydrous calcium sulfate at  $37 \pm 2^{\circ}$ C for 24 hours prior to testing.

Testing was performed using a Model 2920 differential scanning calorimeter (TA Instruments, New Castle, DE). Individual specimens were placed in a closed sample pan and subjected to a constant heating rate of 10°C/min. This technique was used to identify residual reactivity in processed specimens, as well as to determine the glass transition temperature of each material. Information was monitored by the attendant computer, and a representative trace was generated for each material (see Fig 2). The peak produced by residual polymerization was integrated to determine the heat released by completion of the reaction, and  $T_g$  was determined by analysis of the downward shift in the heat flow curve. All specimens were tested twice.

## **Dynamic Mechanical Analysis**

Dynamic mechanical analysis was performed using a single specimen from each of the 6 denture base resin systems. Individual specimens were fabricated according to manufacturers' directions and machined to 65 mm  $\times$  10 mm  $\times$  2.5 mm using the materials and techniques described for flexural testing specimens. Specimens were stored in a water bath at 37  $\pm$  2°C for 50 hours. Individual specimens then were removed from the water bath, dried, and tested.

Testing was performed using a Model 2980 Dynamic Mechanical Analyzer (TA Instruments, New Castle, DE). Data were analyzed using the TA Instruments' Universal Analyst software package, which follows standard procedures for determination of peaks and transitions as defined in ASTM D 4065.

Specimens were clamped in a three-point bending configuration and subjected to a cyclic deflection at a frequency of 1 Hz, while the temperature was increased at a rate of 5°C/min. Data were recorded, and a representative trace was generated for each material (see Fig 4). The  $T_g$  of each resin was determined using a standard analysis of the drop in the storage modulus curve. This technique provides temperature values for extrapolated onset, midpoint, and endpoint of the transition. In addition, an estimate of the  $T_g$  was obtained from the loss modulus curve by identification of the temperature at the upper peak of the trace.

#### Adaptation Testing

Resin systems also were evaluated for quality of adaptation using a test-specific master cast (Fig 5). This cast resembled a small dome with a gently curving concavity at its superior surface. Four rounded depressions were evenly spaced around the periphery of the cast. The concavity at the superior surface of the cast was intended to simulate the concavity found at the maxillary posterior palatal seal area. Peripheral depressions were intended to simulate mechanical undercuts, and to prevent displacement of processed resin specimens



**Figure 5.** Master cast used in adaptation testing.

during the deflasking process. Two shallow grooves were positioned to serve as a guide for subsequent sectioning procedures.

Using the selected master cast, a flexible silicone mold was fabricated. In turn, 36 duplicates of the master cast were generated using an ADA Type IV dental stone (Silky Rock, WhipMix Corp., Louisville, KY). The casts were divided into 6 groups, allowing 6 specimens per tested resin.

Subsequently, the peripheral depressions of the master cast were filled using blockout wax. The wax was trimmed to produce a smooth surface consistent with the curvature of the stone cast. A rigid spacer was created on the master cast using a Biostar adaptation apparatus (Scheu Dental, Iserlohn, Germany) and two 1.5-mm thick thermoplastic sheets (Great Lakes Orthodontics, Ltd., Tonawanda, NY). The spacer was then removed from the master cast and tried onto each of the duplicate casts to ensure accurate adaptation.

Individual casts were flasked with the spacer in position, thereby promoting standardization of mold cavities. An ADA Type IV stone (Silky Rock, WhipMix Corp.) was used in all flasking applications. Manufacturers' instructions regarding preparation and flasking were followed.

Upon completion of individual flasking processes, the standardized spacer was removed. Wax elimination was simulated by heating and rinsing each mold with boiling water. Two coats of a separating medium (Al-Cote, Dentsply International, York, PA) were applied to warm stone surfaces and permitted to set.

Resin preparation, placement, and processing were performed in accordance with manufacturers' instructions. After processing, flask assemblies were permitted to cool to room temperature. Processed resin specimens then were recovered on their casts.

Resin specimens then were sectioned through the midline on their respective casts (Fig 6). The sectioning process was accomplished using a Craftsman 9-inch band saw (Sears, Roebuck and Co., Hoffman Estates, IL). Feed rates were carefully controlled to avoid undue heating of resin specimens. Sectioned surfaces were smoothed using a rotary lapping table (LECO Corp., St. Joseph, MI) and a 400-grit abrasive wheel.

At this stage, an Olympus Model SZH-10 stereomicroscope with a digital image analysis package (Olympus Optical Co., Ltd., Tokyo, Japan) was used to measure the gap between resin specimens and the associated casts. Magnification of  $100 \times$  was employed. Measurements were made at the midpoint of the superior (concave) surface and at locations 2.5 mm left and right of the midpoint. Mean gaps were calculated for each specimen and each resin system. Results were analyzed using ANOVA followed by Fisher's least significant difference test.

## Results

#### Sorption, Solubility, and Color Stability

The sorption, solubility, and color stability behavior of all systems satisfied the requirements set forth in ADA Specification No. 12.



Figure 6. Resin specimen and cast after sectioning.

Material	Mean Modulus Value (GPa)	Standard Deviation
Acron MC compression Acron MC injection Lucitone CH compression Lucitone 199 compression Lucitone 199 injection SR Ivocap injection	2.892 2.863 2.762 2.441 2.281 2.523	$\begin{array}{c} 0.032 \\ 0.087 \\ 0.030 \\ 0.033 \\ 0.022 \\ 0.063 \end{array}$

Table 2. Results for Flexural Modulus Testing

#### Flexural Testing

All materials met minimum flexural testing requirements described in ADA Specification No. 12. As previously noted, additional specimens were tested using a mechanical test frame and threepoint bending apparatus. Moduli for individual materials were calculated and are presented in Table 2.

Results of ANOVA indicated a statistically significant difference between mean modulus values (p < 0.0001). Consequently, Fisher's least significant difference test was applied (p < 0.05). The results of these analyses are presented in Table 3. Examination of results indicates statistically significant differences between all groups.

#### Hardness

Mean hardness values for polymerized resin specimens are presented in Table 4. Results of ANOVA indicated the presence of a statistically significant difference in mean hardness (p < 0.0025). There-

 Table 4. Results for Hardness Testing

 Mean Hardness

Material	Mean Hardness Value (Shore D)	Standard Deviation
Acron MC compression Acron MC injection Lucitone CH compression Lucitone 199 compression Lucitone 199 injection SR Ivocap injection	85.00 85.00 83.83 83.50 81.83 82.67	$\begin{array}{c} 0.87 \\ 0.50 \\ 0.29 \\ 0.50 \\ 0.29 \\ 1.61 \end{array}$

fore, Fisher's least significant difference test was performed (p < 0.05). Results of these analyses are presented in Table 5.

# Differential Scanning Calorimetry

Differential scanning calorimetry results are summarized in Table 6. The first scan was designed to permit evaluation of the polymerized resins. Glass transition temperatures and representative exotherms (in Joules/gram) were determined for each resin. In turn, exotherm data were used to determine the relative completeness of polymerization for each resin. Subsequently, each specimen was subjected to a second scan. Second-scan data were collected to determine the characteristics of the representative polymers in a fully polymerized and dry state.

Examination of data indicates all polymerized specimens exhibited glass transition temperatures of approximately 100°C. First-scan results indicate the presence of comparatively large exotherms for Lucitone 199 injection-molded and SR-Ivocap resins. Such exotherms are related

Table 3. Statistical Comparison of Flexural Modulus Results

	DF	Sum of Squar	es Mean Square	F-Value	p-Value	Lambda	Power
ANOVA (Mod Type Residual	lulus) 5 30	2.183 0.075	$0.437 \\ 0.002$	175.476	< 0.0001	877.379	1.000
Acron MC Compression	Acr Inj	on MC jection	Lucitone CH Compression	SR-Ivocap Injection	Lucitone 199 Compression	Luc It	itone 199 njection

Fisher's Protected Least Significant Difference (Modulus)

Note. A common underline indicates results with no statistically significant difference at p < 0.05.

		5 1	1120an 840		p-v $uuv$	Lambaa	1 00001
ANOVA (Haro Type Residual	dness) 5 12	23.903 8.000	4.781 0.667	7.171	0.0025	35.854	0.976
Acron MC Compression	Acro Inje	n MC ection	Lucitone CH Compression	Lucitone 199 Compression	SR-Ivocap Injection	Lucit Inj	one 199 ection

Table 5. Statistical Comparison of Hardness Results

Note. A common underline indicates results with no statistically significant difference at p < 0.05.

to the amount of unreacted monomer in each material. Consequently, Lucitone 199 injectionmolded and SR-Ivocap resins exhibited relatively large amounts of unreacted methyl methacrylate (i.e., monomer). Comparatively small exotherms were noted for all remaining resins.

Second-scan results yielded relatively consistent glass transition temperatures for all resins.

#### Dynamic Mechanical Analysis

The results of dynamic mechanical analysis are presented in Table 7. The dynamic moduli of individual materials at 30 and 50°C are displayed.

Storage modulus curves for all resin systems are presented in Figure 7. These curves describe the storage moduli of individual materials over a defined temperature range. Higher values are associated with more rigid resins, whereas lower values represent more flexible resins.

#### Adaptation

Mean gap results are presented in Table 8. ANOVA results indicated a statistically significant difference among these groups (p < 0.0001). Con-

**Table 6.** Results for Differential Scanning Calorimetry(DSC) Testing

Material	First	First Scan	Second
	Scan	Exotherm	Scan
	T <sub>g</sub> (°C)	(J/g)	T <sub>g</sub> (°C)
Acron MC compression	$101.1 \\ 101.0 \\ 102.1 \\ 102.7 \\ 96.0 \\ 94.9$	0.68	102.5
Acron MC injection		1.35	104.7
Lucitone CH compression		0.91	103.6
Lucitone 199 compression		2.34	103.2
Lucitone 199 injection		6.87	103.0
SR Ivocap injection		7.80	104.4

sequently, Fisher's least significant difference test was utilized (p < 0.05). Results of these analyses are presented in Table 9.

## Discussion

In this investigation, a combination of mechanical and thermal testing procedures was used to characterize specific properties of 6 commonly used denture base resins. By comparing the results of individual testing procedures, several assertions can be made.

Clinically, the adaptation of denture bases to the associated tissues is of critical importance.<sup>22,23</sup> In this investigation, Acron MC compressionmolded and Acron MC injection-molded resins displayed the best adaptation to standardized casts. Lucitone Ch, Lucitone 199 compressionmolded, Lucitone 199 injection-molded, and SR-Ivocap resins did not display the same degree of adaptation. Hence, the improved adaptation of microwaveable resins must be considered a potential advantage.

The flexure of denture base resins is also important.<sup>24,25</sup> As a rule, materials with enhanced flexural properties display greater toughness and

 Table 7. Results of Dynamic Mechanical Analysis (DMA) Testing

Material	Dynamic Modulus @ 30°C (GPa)	Dynamic Modulus @ 50°C (GPa)
Acron MC compression Acron MC injection Lucitone CH compression Lucitone 199 compression Lucitone 199 injection SR Ivocap injection	3.329 3.120 3.087 3.026 2.790 2.783	$\begin{array}{c} 2.879 \\ 2.785 \\ 2.703 \\ 2.665 \\ 2.353 \\ 2.374 \end{array}$



Figure 7. DMA trace indicating results for all materials.

survivability in denture base applications. For these reasons, rubber-modified resins such as Lucitone 199 have been well received as denture base materials.

All resins included in this investigation met minimum flexural testing requirements prescribed by the ADA. These results are in general agreement with the findings of Smith et al.<sup>26</sup> Dynamic mechanical analysis results were also consistent with the results of flexural testing. Nevertheless, the limited number of dynamic mechanical analysis specimens used in this investigation permits observational findings only.

It was not surprising that the Lucitone 199 compression- and injection-molded resins displayed the lowest flexural moduli. Lucitone 199 is a rubber-modified resin and would be expected to exhibit greater elasticity than unmodified resins.

It is interesting to note that injection-molded resins were more resilient than their compressionmolded counterparts. Injection-molded resins

Table 8. Results for Adaptation Testing

Material	Mean Gap (mm)	Standard Deviation
Acron MC compression Acron MC injection Lucitone CH compression Lucitone 199 compression Lucitone 199 injection SR Ivocap injection	$\begin{array}{c} 0.139 \\ 0.129 \\ 0.159 \\ 0.161 \\ 0.165 \\ 0.163 \end{array}$	$\begin{array}{c} 0.016 \\ 0.004 \\ 0.010 \\ 0.017 \\ 0.012 \\ 0.010 \end{array}$

generally require a greater monomer content to improve flow characteristics and facilitate filling of the mold cavity. This often results in additional unreacted monomer within a polymerized resin. In turn, the unreacted monomer may serve as a plasticizer, thereby increasing the resiliency of the polymerized denture base resin.

A review of differential scanning calorimetry results suggests that Lucitone 199 injectionmolded and SR-Ivocap injection-molded resins contained relatively large amounts of unreacted monomer following polymerization. The increased amounts of unreacted monomer may account for at least part of the resiliency in the injection-molded resins.<sup>27</sup> Nevertheless, differential scanning calorimetry results must be interpreted with caution due to the limited number of samples included in this investigation.

Durometer results were consistent with the general effects of rubber modification and unreacted monomer content. The results of hardness testing are similar to the findings of Smith et al and Loh et al.<sup>26,28</sup> Nevertheless, the importance of surface hardness is unclear and should be interpreted with caution.

The completeness of polymerization is significant for 2 major reasons.<sup>24-29</sup> First, the degree of polymerization affects the mechanical and geometric properties of resultant prostheses.<sup>29-31</sup> Second, unreacted monomer may produce undesirable effects in the human body.<sup>32-34</sup> Consequently, resins displaying greater degrees of polymerization may provide substantial clinical advantages.

## Conclusions

The results of mechanical and thermal testing support the following generalizations:

- 1. The microwaveable resins (Acron MC compression-molded and injection-molded) displayed better adaptation, greater stiffness, and greater surface hardness than other denture base resins included in this investigation.
- 2. The inclusion of elastomeric toughening agents (i.e., rubber-based modifiers) yielded decreased stiffness, decreased surface hardness, and decreased  $T_g$  values.

	DF	Sum of Sqi	ares Mean Squa	are F-Value	p-Value	Lambda	Power
ANOVA (Ada Type Residual	ptation) 5 30	$0.007 \\ 0.005$	0.001 1.519E-4	8.942 ł	< 0.0001	44.710	1.000
Acron MC Compression	Acre Inj	on MC ection	Lucitone CH Compression	Lucitone 199 Compression	SR-Ivocap Injection	Luc It	itone 199 njection

Table 9. Statistical Comparison of Adaptation Results

Note. A common underline indicates results with no statistically significant difference at p < 0.05.

### References

- Sweeney WT: Acrylic resins in prosthetic dentistry. Dent Clin North Am 1958;2:539-601
- Anthony DH, Peyton FA: Dimensional accuracy of various denture base materials. J Prosthet Dent 1962;12:67-81
- Woelfel JB: Newer materials and techniques in prosthetic resin materials. Dent Clin North Am 1971;15:67-79
- Chiang BK: Polymers in the service of prosthetic dentistry. J Dent 1984;12:203-214
- Anusavice KJ: Denture base resins: Technical considerations and processing techniques. In: Phillips' Science of Dental Materials, vol 1, ed 10. Philadelphia, PA, W.B. Saunders, 1991, pp 237-271
- Garfunkel E: Evaluation of dimensional changes in complete dentures processed by injection-pressing and the pack-and-press technique. J Prosthet Dent 1983;50:757-761
- Strohaver RA: Comparison of changes in vertical dimension between compression and injection molded complete dentures. J Prosthet Dent 1989:62; 716-718
- Sanders JL, Levin B, Reitz PV: Porosity in denture acrylic resins cured by microwave energy. Quintessence Int 1987; 18:453-456
- Shlosberg SR, Goodacre CJ, Munoz CA, et al: Microwave energy polymerization of poly(methyl methacrylate) denture base resin. Int J Prosthodont 1989;2:453-458
- Neihart TR, Li SH, Flinton RJ: Measuring fracture toughness of high-impact poly(methyl methacrylate) with the short rod method. J Prosthet Dent 1988;60:249-253
- Stafford GD, Bates JF, Huggett R, et al: A review of the properties of some denture base polymers. J Dent 1980;8:292-306
- Craig RG, Powers JM, Peyton FA: Differential thermal analysis of commercial and dental waxes. J Dent Res 1967;46:1090-1097
- Brauer GM, Termini DJ, Burns CL: Characterization of components of dental materials and components of tooth structure by differential thermal analysis. J Dent Res 1970;49:100-110
- Lloyd CH: The determination of the specific heats of dental materials by differential thermal analysis. Biomaterials 1981;2:179-181

- Kotsiomiti E, McCabe JF: Stability of dental waxes following repeated heatings. J Oral Rehabil 1995;22:135-143
- McCabe JF, Wilson HJ: The use of differential scanning calorimetry for the evaluation of dental materials: II. Denture base materials. J Oral Rehabil 1980;7:235-243
- Ohyama A, Imai Y: Differential scanning calorimetric study of acrylic resin powders used in dentistry. Dental Mater J 2000;19:346-351
- Clarke RL: Dynamic mechanical thermal analysis of dental polymers: I. Heat-cured poly(methyl methacrylate)-based materials. Biomaterials 1989;10:494-498
- Clarke RL: Dynamic mechanical thermal analysis of dental polymers: II. Bis-phenol A-related resins. Biomaterials 1989;10:549-552
- Clarke RL: Dynamic mechanical thermal analysis of dental polymers: III. Heterocyclic methacrylates. Biomaterials 1989;10:630-633
- Tamareselvy K, Rueggeberg FA: Dynamic mechanical analysis of two crosslinked copolymer systems. Dent Mater 1994;10:290-297
- 22. Zarb GA, McGivney GP: Completing the rehabilitation of the patient. In: Boucher's Prosthodontic Treatment for Edentulous Patients, vol 1, ed 11. St. Louis, MO, Mosby, 1997, pp 358-389
- Rahn AO, Heartwell CM: Denture insertion. In: Textbook of Complete Dentures, vol 1, ed 5. Baltimore, MD, Williams & Wilkins, 1993, pp 387-401.
- Stafford GD, Handley RW: Transverse bend testing of denture base polymers. J Dent 1975;3:251-255
- Batchelor RF: Transverse test for non-metallic denture base materials. A modified and improved method. Br Dent J 1969;126:30-31
- 26. Smith LT, Powers JM, Ladd D: Mechanical properties of new denture resins polymerized by visible light, heat, and microwave energy. Int J Prosthodont 1992;5:315-320
- Oku J: Impact properties of acrylic denture base resin: II. Effect of temperature and residual monomer on impact characteristics. Dental Mater J 1989;8:186-193
- Loh PL, Munoz CA, Goodacre CJ, et al: An evaluation of microwave-polymerized resin bases for removable partial dentures. J Prosthodont 1996;5:259-265
- Anusavice KJ: Chemistry of synthetic resins. In: Phillips' Science of Dental Materials, vol 1, ed 10. Philadelphia, PA, W.B. Saunders, 1991, pp 211-235

- Rosen SL: Plastics. In: Fundamental Principles of Polymeric Materials, vol 1, ed 1. New York, NY, John Wiley, 1982, pp 302-313
- Callister WD: Characteristics, application, and processing of polymers. In: Materials Science and Engineering: An Introduction, vol 1, ed 2. New York, John Wiley, 1991, pp 487-527
- Hensten-Pettersen A, Wictorin L: The cytotoxic effect of denture base polymers. Acta Odontol Scand 1981;39:101-106
- 33. Schuster GS, Lefebvre CA, Dirksen TR, et al: Relationships between denture base resin cytotoxicity and cell lipid metabolism. Int J Prosthodont 1995;8:580-586
- 34. Cimpan MR, Matre R, Cressey LI, et al: The effect of heat- and auto-polymerized denture base polymers on clonogenicity, apoptosis, and necrosis in fibroblasts: Denture base polymers induce apoptosis and necrosis. Acta Odontol Scand 2000;58:217-228