Evaluation of alternative polymer bracket materials

Julia Krauss,a Andreas Faltermeier,b Michael Behr,c and Peter Proffd
Regensburg, Germany

Introduction: Polymer brackets still have some disadvantages because of decreased wear resistance and hardness. The aim of this study was to investigate the mechanical properties of alternative bracket polymers; urethane-dimethacrylate, high-density polyethylene, and an experimental bracket polymer (EBP) consisting of polyethylene and a copolymer were tested. Polycarbonate and polyoxymethylene brackets served as controls. Methods: The mechanical properties of urethane-dimethacrylate, high-density polyethylene, EBP, polycarbonate, and polyoxymethylene bracket materials were evaluated after thermocycling (6000 × 5°C-55°C) in a mastication device before testing. Three medium-wear, fracture toughness, and Vickers hardness tests were performed. Results: High-density polyethylene had the highest values of wear and the lowest values of fracture toughness and Vickers hardness. The urethane-dimethacrylate bracket material and the EBP had better mechanical properties than polycarbonate. The polyoxymethylene bracket material had the highest values of fracture toughness and Vickers hardness, and the lowest values of wear compared with the other investigated polymers. Conclusions: High-density polyethylene seems to be unsuitable as bracket material because it demonstrated excessive wear and insufficient fracture toughness. Polyoxymethylene had the best performance during mechanical testing. (Am J Orthod Dentofacial Orthop 2010;137:362-7)

Nowadays, requests for esthetic fixed orthodontic appliances have increased. More young patients want an aesthetic appearance during treatment with fixed appliances. In addition, the demand for adult treatment is growing in orthodontics. Therefore, the introduction of esthetic brackets has been a blessing for some patients. Esthetic bracket materials are ceramics and various polymers. The advantages of ceramic brackets include color stability and great strength. On the other hand, excessive wear of enamel surfaces on opposing teeth has been observed during treatment with ceramic brackets.1 Damage to the enamel during removal of the brackets and bracket breakage because of brittleness were also reported.1

In the 1970s, the first plastic brackets were manufactured from polycarbonate.2 Later, polyurethane, fiber-reinforced, and filler-reinforced brackets became available. In 1997, a German patent was issued for a new plastic bracket of polyoxymethylene.3 Despite these innovations, plastic brackets still have some disadvantages because of their decreased mechanical properties compared with ceramic brackets and their inability to withstand the torquing forces generated by rectangular wires.1 In addition, water sorption of plastic brackets could cause a plasticizing effect. Plasticizing decreases the properties of the polymeric structure in a wet environment.4,5 Therefore, further efforts are necessary to improve the mechanical properties of plastic brackets to offer patients cost-effective, tooth-colored plastic brackets that are easier to handle than ceramic brackets.

The aim of the study was to compare 3 experimental bracket polymers with polyoxymethylene and polycarbonate bracket materials. The first experimental bracket polymer (EBP) is well established in bearing technology and consists of a polyethylene and a copolymer. Additionally, the characteristics of high-density polyethylene and urethane-dimethacrylate were studied for use as bracket materials in orthodontics. To simulate the moisture of saliva and the temperature changes in the oral environment, all samples were thermocycled in an artificial oral environment. All bracket polymer groups were alternately flooded every 2 minutes with warm (55°C) and cold (5°C) distilled water for 6000 cycles in a mastication device to initiate plasticizing of the polymers before testing.6 Then, fracture toughness, which is the resistance of the polymer to crack...
expansion and wear, was determined with a 3-medium wear test device. Vickers hardness of the bracket materials was also calculated.

MATERIAL AND METHODS

A total of 100 rectangular beams (20 per group) were manufactured with the dimensions of 36 × 8 × 4 mm (length × width × thickness). Five polymer groups were investigated: group 1, polyoxymethylene; group 2, polycarbonate; group 3, EBP; group 4, high-density polyethylene; and group 5, urethane-dimethacrylate. The surface of each beam was ground with sand paper (800 grit) first. Then, all beams were polished.

Before fracture toughness was tested, all beams were thermocycled in a mastication device (6000 cycles, 800 grit). Then, all beams were polished. The surface of each beam was ground with sand paper polyethylene; and group 5, urethane-dimethacrylate. Fracture toughness (MPa m\(^{1/2}\)) was calculated for each sample according to the method of Williams and Cawood.\(^7\)

Fracture toughness depends on fracture load, dimensions of the samples, notch length, and the support distance of the 3-point bending test. Fracture toughness was calculated for each sample according to the method of Williams and Cawood.\(^7\)

A 3-medium wear test was performed by using a wear testing machine (Willytec, Munich, Germany). Ten samples of the 5 polymer groups were placed adhesively in the individual chambers of the round Academic Center Tandheelkunde Amsterdam sample holder. The tests were performed by using an abrasion medium consisting of rice (120 g) and millet seed shells (30 g) that were ground in a rotating blade grinder (Moulinette, Moulinex, Alencon, France) for 60 seconds and mixed with distilled water (275 mL). A total of 200,000 cycles were completed by using an antagonist wheel with a press-on load of 15 N. Every 50,000 cycles, the abrasion medium was replaced. A wear track on the sample wheel was caused by the antagonist wheel. The trace depth of this wear track was determined by using a roughness testing device (Perthometer S6P, Perthonprüf, Göttingen, Germany).

The bracket materials were loaded by a pyramid-shaped loading die (load weight, 0.5 kg) of the Vickers hardness measurement device (model B3212001, Zwick). The loading time was set to 60 seconds. The pyramid-shaped indentation in the resin depended on the hardness of the bracket. Vickers hardness is proportional to the quotient of applied load and the area of the indentation and was determined with the following formula.\(^8\)

\[
VH = 0.102 \frac{F}{A} = 0.102 \frac{F \cdot \sin \frac{180^\circ}{d^2}}{d^2}
\]

where \(VH\) is Vickers hardness, \(F\) is load, \(A\) is area, and \(d\) is diagonal of indention.

Statistical analysis

Medians and 25% and 75% percentiles were calculated. Statistical differences were investigated by using the Mann-Whitney U test (the level of significance was set at \(P = 0.05\)).

RESULTS

Median values and standard deviations for the bracket polymers are given in Table I. With the exception of polycarbonate and EBP, all bracket polymers showed significantly different values...
for fracture toughness (Table II, Fig 1). The highest median values of fracture toughness were determined for the polyoxymethylene brackets (Table I). Polycarbonate and EBP bracket materials exhibited no significant difference in fracture toughness. The urethane-dimethacrylate bracket material had significantly higher values than polycarbonate and EBP but significantly lower values than polyoxymethylene.

With more cycles, all bracket materials showed greater wear tracks. Almost all polymers showed significantly different amounts of abrasion (Table III). The polyoxymethylene and the urethane-dimethacrylate bracket materials had the lowest abrasion values after 200,000 cycles (Fig 2). High-density polyethylene had the greatest wear compared with the other polymers, with median wear of 238.5 ± 32.67 μm (Table I).

The lowest Vickers hardness values were determined for polycarbonate and high-density polyethylene bracket materials (Table I, Fig 3). Polyoxymethylene showed significantly higher Vickers hardness values compared with the other polymers, with median values of 18.23 ± 0.90 (Tables I and IV).

**DISCUSSION**

Regardless of the esthetic advantages of polymeric brackets, their use is still limited because of decreased wear resistance and hardness, and insufficient color stability. To improve their properties, 3 methods are possible: reinforcement with other materials (fillers and fibers), chemical modification of the polymer, and alternative polymers. We evaluated alternative polymers such as urethane-dimethacrylate, high-density polyethylene, and EBP. Urethane-dimethacrylate was chosen as an experimental bracket polymer because it has some advantages: low viscosity, low water sorption, and great toughness. Urethane-dimethacrylate is commonly used in restorative dentistry as an additive to the well-known monomer Bis-GMA. The choice of a monomer system is an important factor influencing the properties of composites. High-density polyethylene is characterized by fragile ramified polymeric chains. The density of the material is 0.95 g per cubic
Fig 2. Wear (μm) after 200,000 cycles of polymer brackets (medians, 25% and 75% percentiles, minimums, and maximums). POM, Polyoxymethylene; PC, polycarbonate; EBP, experimental bracket polymer; HDPE, high-density polyethylene; UDMA, urethane-dimethacrylate.

Fig 3. Vickers hardness (no units) of polymer brackets (medians, 25% and 75% percentiles, minimums, and maximums). POM, Polyoxymethylene; PC, polycarbonate; EBP, experimental bracket polymer; HDPE, high-density polyethylene; UDMA, urethane-dimethacrylate.
different material groups could be oral cavity, the temperatures on interfaces between different chemical bonding forces (van der Waals forces) can penetrate into the polymer. As a result, the second-order reactions in in-vitro investigations. Therefore, it is obvious that further work is necessary to investigate the role of the polymer matrix on the clinical behavior of orthodontic brackets.

**CONCLUSIONS**

High-density polyethylene seems to be unsuitable as bracket material, because it obviously has lower fracture toughness and wear resistance than the other tested polymers. Urethane-dimethacrylate and EBP demonstrated better mechanical properties than polycarbonate. Nevertheless, polyoxymethylene performed the best during mechanical testing in this study compared with the other polymers.

Despite the results of this in-vitro study, the clinical performance of brackets depends on diverse synergistic effects in the oral environment that cannot be simulated in in-vitro investigations. Therefore, it is obvious that further work is necessary to investigate the role of the polymer matrix on the clinical behavior of orthodontic brackets.

**Table IV. Statistical analysis of Vickers hardness, Mann-Whitney U test P values**

<table>
<thead>
<tr>
<th></th>
<th>POM</th>
<th>PC</th>
<th>EBP</th>
<th>HDPE</th>
<th>UDMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>POM</td>
<td>–</td>
<td>0.005</td>
<td>0.013</td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>PC</td>
<td>–</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>EBP</td>
<td>–</td>
<td>0.005</td>
<td>0.005</td>
<td>0.009</td>
<td></td>
</tr>
<tr>
<td>HDPE</td>
<td>–</td>
<td>–</td>
<td>0.005</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UDMA</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

POM, Polyoxymethylene; PC, polycarbonate; EBP, experimental bracket polymer; HDPE, high-density polyethylene; UDMA, urethane-dimethacrylate.

centimeter. This polymer is widely used in industry for the manufacturing of pumps and tubs. EBP is well established in bearing technology and offers low friction and low abrasion. EBP consists of 90% polyethylene and an extensible copolymer (10%). In this study, mechanical properties of various bracket polymers were tested after thermocycling. According to another study, the temperature of food is between –8 °C and 81 °C. It was concluded that, in the oral cavity, the temperatures on interfaces between different material groups could be 5 °C to 52 °C. Increased water sorption is most likely the main factor that affects the long-term stability of the polymeric structure. Water can penetrate into the polymer. As a result, the secondary chemical bonding forces (van der Waals forces) between the polymer chains are reduced, and the mechanical properties of the resin decrease. This plasticizing effect affects mainly the properties of the bracket. Daub et al stated that the amount of water absorbed by the polymer and the rate of absorption are controlled by diffusion and depend mostly on material factors. Consequently, we used thermocycling (6000 × 5 °C-55 °C) in a mastication device before material testing to simulate cyclic stress at 2 temperature extremes and to reproduce the water sorption expected in the oral environment.

Wear components in the oral cavity are erosive and contact sliding wear with a third medium—natural food substances. In prosthetic dentistry, much literature is available about the wear resistance of polymers and composites. In the orthodontic literature, there are only a few articles about the mechanical properties of polymer brackets. Faltermeier et al demonstrated that urethane-dimethacrylate brackets reinforced with silicon dioxide filler showed an obvious trend for improved mechanical properties compared with unfilled urethane-dimethacrylate brackets. Zinelis et al compared roughness, hardness, and wear resistance of polymer bracket raw materials. To determine wear resistance, a scratch test was performed, and Vickers hardness was tested. They described reduced mechanical properties of polymeric materials compared with polycrystalline alumina and the inappropriateness of ultra high molecular weight polyethylene. Additionally, they observed improved wear resistance of polyoxymethylene brackets compared with polycarbonate brackets. However, they used a scratch test for wear resistance testing. In our study, we used the 3-medium wear test of deGee and Pallav, containing an abrasion medium to simulate the situation in the oral cavity. Additionally, Vickers hardness and fracture toughness were tested. Fracture toughness describes the resistance of the polymer against crack expansion.

Analysis of the data obtained in our study offers insight into the influence of the raw material of brackets on its mechanical properties. According to Zinelis et al, raw materials were tested to exclude any influences of bracket design, size, and morphologic factors in the measurements. The highest values of fracture toughness and Vickers hardness were found with polyoxymethylene as the raw material. Additionally, this polymer had the lowest wear compared with the other materials. Polyoxymethylene seems to offer significantly better mechanical properties than polycarbonate, which is still used as bracket material. Our study confirmed the results of Zinelis et al, who reported that polyethylene was inappropriate as a bracket material. We also studied high-density polyethylene. However, its performance was unsuitable for brackets because of its excessive wear and insufficient fracture toughness. Urethane-dimethacrylate and EBP had better mechanical properties than polycarbonate. Nevertheless, the polyoxymethylene bracket material performed the best during mechanical testing in this study compared with the other polymers.

In this study, mechanical properties of various polymer brackets were tested after thermocycling. According to another study, the temperature of food is between –8 °C and 81 °C. It was concluded that, in the oral cavity, the temperatures on interfaces between different material groups could be 5 °C to 52 °C. Increased water sorption is most likely the main factor that affects the long-term stability of the polymeric structure. Water can penetrate into the polymer. As a result, the secondary chemical bonding forces (van der Waals forces) between the polymer chains are reduced, and the mechanical properties of the resin decrease. This plasticizing effect affects mainly the properties of the bracket. Daub et al stated that the amount of water absorbed by the polymer and the rate of absorption are controlled by diffusion and depend mostly on material factors. Consequently, we used thermocycling (6000 × 5 °C-55 °C) in a mastication device before material testing to simulate cyclic stress at 2 temperature extremes and to reproduce the water sorption expected in the oral environment.

Wear components in the oral cavity are erosive and contact sliding wear with a third medium—natural food substances. In prosthetic dentistry, much literature is available about the wear resistance of polymers and composites. In the orthodontic literature, there are only a few articles about the mechanical properties of polymer brackets. Faltermeier et al demonstrated that urethane-dimethacrylate brackets reinforced with silicon dioxide filler showed an obvious trend for improved mechanical properties compared with unfilled urethane-dimethacrylate brackets. Zinelis et al compared roughness, hardness, and wear resistance of polymer bracket raw materials. To determine wear resistance, a scratch test was performed, and Vickers hardness was tested. They described reduced mechanical properties of polymeric materials compared with polycrystalline alumina and the inappropriateness of ultra high molecular weight polyethylene. Additionally, they observed improved wear resistance of polyoxymethylene brackets compared with polycarbonate brackets. However, they used a scratch test for wear resistance testing. In our study, we used the 3-medium wear test of deGee and Pallav, containing an abrasion medium to simulate the situation in the oral cavity. Additionally, Vickers hardness and fracture toughness were tested. Fracture toughness describes the resistance of the polymer against crack expansion.

Analysis of the data obtained in our study offers insight into the influence of the raw material of brackets on its mechanical properties. According to Zinelis et al, raw materials were tested to exclude any influences of bracket design, size, and morphologic factors in the measurements. The highest values of fracture toughness and Vickers hardness were found with polyoxymethylene as the raw material. Additionally, this polymer had the lowest wear compared with the other materials. Polyoxymethylene seems to offer significantly better mechanical properties than polycarbonate, which is still used as bracket material. Our study confirmed the results of Zinelis et al, who reported that polyethylene was inappropriate as a bracket material. We also studied high-density polyethylene. However, its performance was unsuitable for brackets because of its excessive wear and insufficient fracture toughness. Urethane-dimethacrylate and EBP had better mechanical properties than polycarbonate. Nevertheless, the polyoxymethylene bracket material performed the best during mechanical testing in this study compared with the other polymers.

Despite the results of this in-vitro study, the clinical performance of brackets depends on diverse synergistic effects in the oral environment that cannot be simulated in in-vitro investigations. Therefore, it is obvious that further work is necessary to investigate the role of the polymer matrix on the clinical behavior of orthodontic brackets.
REFERENCES