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Impact energy absorption of three mouthguard materials in three environments

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Abstract – The objective of this study was to compare the impact energy absorption of three mouthguard materials in three environments. Thirty specimens with 12.7 cm × 12.7 cm × 4 mm dimensions were prepared for each material: ethylene vinyl acetate (EVA, T&S Dental and Plastics), Pro-form™ (Dental Resources Inc), and PolyShok™ (Sportsguard Laboratories). Ten specimens of each material were conditioned for 1 h at 37°C in three environments: dry (ambient) condition, deionized water and artificial saliva. Specimens were impacted at 20 mph by a 0.5-inch diameter indenter containing a force transducer (Dynatup Model 9250 HV, Instron Corp), based upon ASTM Standard D3763. Energy absorption was determined from the area under the force–time curve during impact (approximately 5 or 7 ms depending on the material). Groups were compared using ANOVA and the Tukey test. Energy absorption values, normalized to specimen thickness (mean ± SD in J mm^{-1}), were: (i) Dry: EVA 4.73 ± 0.27, Pro-form™ 3.55 ± 0.25, PolyShok™ 6.32 ± 0.24; (ii) DI water: EVA 4.82 ± 0.40, Pro-form™ 3.78 ± 0.33, PolyShok™ 5.87 ± 0.38; (iii) Artificial saliva: EVA 5.63 ± 0.49, Pro-form™ 4.01 ± 0.54, PolyShok™ 6.37 ± 0.55. PolyShok™ was the most energy-absorbent material in all three environments. EVA was significantly more impact resistant than Pro-form™ in all three environments. EVA and Pro-form™ performed significantly better after saliva conditioning than dry or water conditioned, but PolyShok™ did not show any difference in energy absorption when conditioned in any of the three environments. Characteristic deformation patterns from impact loading were observed with an SEM for each material. The superior energy absorption for PolyShok™ is attributed to the polyurethane additive.

The use of mouthguards has long been promoted as a significant way of reducing the incidence of sports and recreational activity related injuries (1). The American Dental Association recognizes the preventive value of orofacial protection and recommends the use of mouthguards in 29 sports/exercise activities (2). Mouthguards can act as a buffer from trauma and provide a degree of protection for both the mouth's soft tissues (lips, gums, and tongue) and hard tissues (teeth and alveolar bone), as well as protection from brain injuries (3). The ability to protect the mouth is highly dependent on the ability of the mouthguard to act as a shock absorber and absorb the force that would otherwise be transmitted to the teeth (4). There are no international standards set for the materials used in the fabrication of mouthguards. However, it is essential that these materials have sufficient energy absorption to dissipate impact forces under clinical conditions (5).

Because of their ease of fabrication and low cost, the most common mouthguards typically used are stock and mouth-formed ('boil and bite'), made from EVA (6). An increase in the education of coaches, athletes, and parents has led to a rise in custom-fabricated mouthguards. This has helped to encourage dental innovation, leading to advancements in design and materials to optimize their energy absorption characteristics.

While studies have shown that thicker mouthguards can withstand larger forces (7–9), thick mouthguards are uncomfortable and can result in decreased ability to breathe and speak. Because patient comfort dictates compliance, 4 mm has been selected as the optimal mouthguard thickness to allow comfort without compromising protection (7). Numerous efforts including laminant layering, air-filled cavities, sorbathane inserts, and hard acrylic inserts, have been made to find a mouthguard design with adequate thickness to provide protection (10–14).

There are several mechanical and physical properties that can affect the protective ability of a mouthguard, such as tensile strength, hardness, stiffness, tear strength, and water absorption. Most important is the ability to absorb energy and reduce forces transmitted to the teeth. There have been numerous studies that have evaluated

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the impact resistance of mouthguards and the effectiveness of different variations in their material composition by using a pendulum, an indenter, or dropped-weight apparatus (5, 7, 10, 11, 15–23).

The majority of *in vitro* tests evaluating the impact resistance of mouthguard materials have been conducted in a dry environment at room temperature. In the oral cavity, mouthguards are subjected to varying degrees of moisture saturation as well as to a temperature that closely mimics body temperature. As the mouthguard material absorbs moisture, its mechanical properties may change and affect its ability to withstand forces. Coto et al. reported that EVA showed improved mechanical responses as a result of exposure to artificial saliva solution (9). Recent impact test studies by Mendel et al. also suggest that mouthguard materials behave differently when conditioned in aqueous and dry environments (24–26). Meng et al. determined from differential scanning calorimetry that critical changes in EVA crystal formation occur near body temperature and could have significant effects on energy absorption potential (27).

The purpose of the present investigation was to evaluate the effect of conditioning environment on the energy absorption characteristics of the three mouthguard materials previously studied by Mendel et al. (24–26). In this investigation, these materials were conditioned at body temperature in three environments: dry (ambient air), deionized water and artificial saliva. The results of this investigation will aid in selecting the optimal material to fabricate mouthguards.

Materials and methods

The three commercially available mouthguard materials previously used by Mendel et al. (24–26) were selected for testing: a conventional EVA (Keystone Industries, Cherry Hill, NJ, USA); Pro-form^{TM} (Dental Resources Inc, Delano, MN, USA), another EVA thermoplastic material; and PolyShok^{TM} (Sportsguard Laboratories, Kent, OH, USA), an EVA product containing polyurethane. All materials were purchased directly from the manufacturers, verified to be from the same production batch, and tested as received.

All materials were processed according to manufacturer recommendations for conventional mouthguard production. Each standard 12.7 cm × 12.7 cm × 4 mm sheet was heated at uniform temperature until there was a 3-cm droop, as verified by a wire jig, and then drawn over a master stone model of 7.5 cm × 7.5 cm × 2.5 cm dimensions representing the dental arch. After cooling for 1 h, the sheet of material was cut into specimens of approximately 7.5 cm × 7.5 cm dimensions. The nominal starting thickness of 4 mm for the as-manufactured materials decreased during the processing used to prepare the test specimens.

The impact properties of the molded mouthguard material samples were tested with an instrumented impact tester (Dynatup Model 9250 HV, Instron Corp, Canton, MA, USA). The pneumatic clamping fixture of the drop-tower apparatus on the Instron machine was set with a 3.0-inch ring opening on the top and a bottom support ring with a diameter opening of approximately 1.5 inches. Stop blocks set on top of spacers were mounted on the base of the tower to arrest the downward motion of the drop weight that provided the impact loading. The impact-testing protocol was based upon ASTM Standard D3763 (28), which was developed to determine the high-speed puncture properties of plastics. Specimens that were conditioned in deionized water or artificial saliva (Roxane Laboratories, Columbus, OH, USA) at 37°C were removed from the liquid and immediately placed in a test chamber at 37°C where they were loaded at 20 mph by a 0.5-inch diameter round-tipped indenter (striker) containing a force transducer. The maximum duration for data collection during each impact test was 10 ms. Energy absorption was determined from the area under the force–time curve during the impact event (ranging from approximately 5 to 7 ms), using the speed of the impacting indenter. Each value of energy absorption was normalized to the measured thickness (NTT) of the specific test specimen. Results were compared using two-way ANOVA and the *post hoc* Tukey test.

An initial power analysis from preliminary data indicated the need for 10 specimens of each material-environment combination to perform statistical comparisons among the sample groups. Ninety specimens were thus tested: three materials (EVA, Pro-form^{TM}, and PolyShok^{TM}) in three environments (dry, deionized water, and artificial saliva), with 10 replicate specimens in each of the nine groups. For the ten specimens of each material that were tested in the dry condition, the samples were allowed to equilibrate first for 1 h in the 37°C chamber. Ten specimens of each material were also conditioned for 1 h in 37°C deionized water and then transferred to the 37°C chamber for immediate testing. Similarly, ten specimens of each material were conditioned for 1 h in the 37°C artificial saliva solution and likewise transferred to the 37°C chamber for immediate testing.

Representative specimens of the three materials were observed with an SEM (Hitachi TM-1000) to investigate differences in deformation and fracture modes during impact loading and determine if differences from exposure to the three conditioning environments were evident. Sample specimens were obtained from near the impact sites, cleaned with deionized water, vacuum sputter-coated with a thin gold film, and observed over a range of magnifications.

Results

Figures 1–3 present the results at 37°C and 20 mph impact speed for 10 replicate specimens of conventional EVA, Pro-form^{TM} and PolyShok^{TM}, respectively, after conditioning for 1 h in 37°C artificial saliva. The general appearance of the impact test plots for each mouthguard material after conditioning in the other two media (1 h in air and deionized water at 37°C) were very similar to Figs 1–3. The left vertical axis on each figure provides the load (units of 1 kN) sensed by the transducer as a function of time (units of 1 ms) on the horizontal axis. These plots show that the load first increases and then decreases with time during the impact event. The right

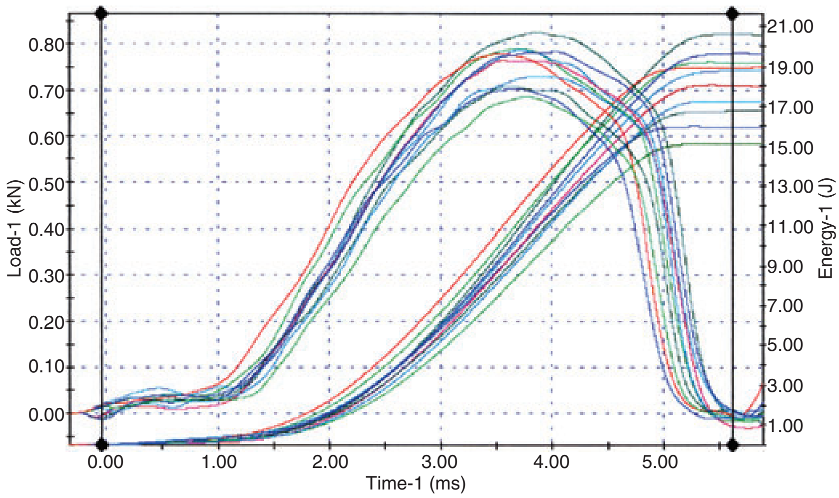

Fig. 1. Impact test results at 20 mph for 10 conventional EVA specimens that had been conditioned for 1 h in artificial saliva at 37°C and then tested at 37°C.

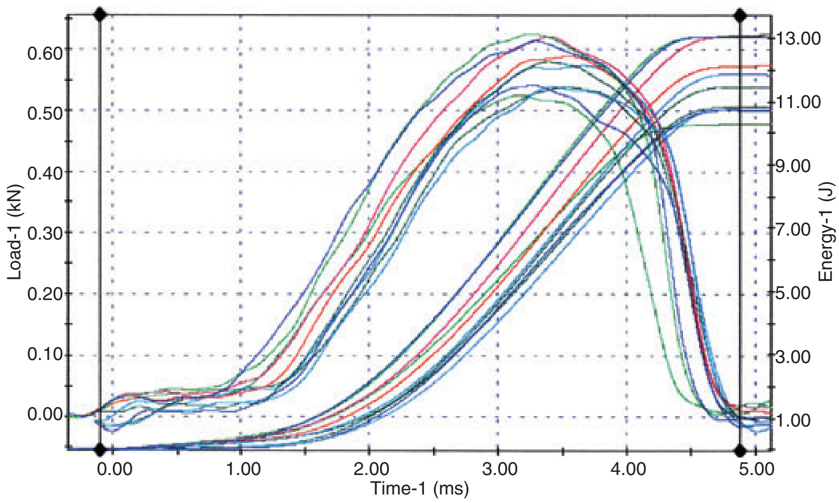

Fig. 2. Impact test results at 20 mph for 10 Pro-form™ specimens that had been conditioned for 1 h in artificial saliva at 37°C and then tested at 37°C.

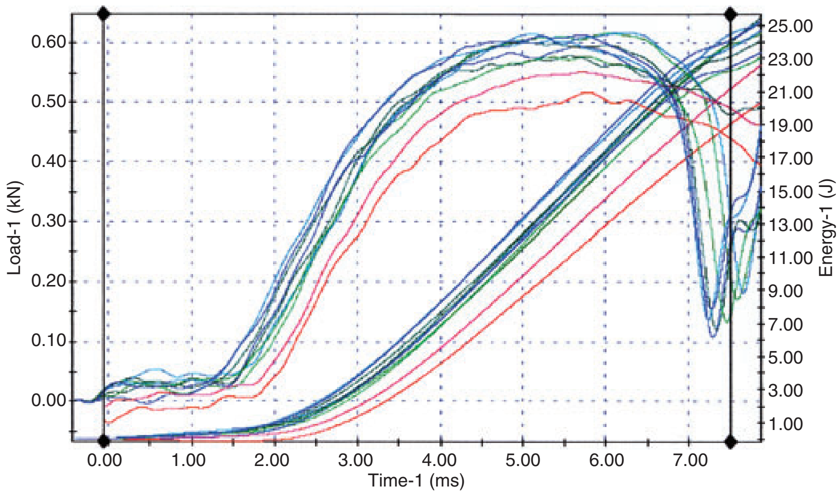

Fig. 3. Impact test results at 20 mph for 10 PolyShok™ specimens that had been conditioned for 1 h in artificial saliva at 37°C and then tested at 37°C.

vertical axis provides the resulting energy absorption (units of 1 J), obtained from the area under the load–time curve, using the distance moved by the striker per unit time. These plots show that the energy absorption increases to a maximum level (appearing as a plateau) during the impact event. The duration of the impact

Table 1. Summary of results for total impact energy absorption, normalized to specimen thickness (NTT), for the three mouthguard materials after conditioning in the three environments. Testing was performed at 37°C and an impact speed of 20 mph, using 3-inch diameter top and 1.5-inch bottom support rings. Before testing, specimens were conditioned in each respective environment for 1 h at 37°C

Material	Specimens (n)	Condition	Mean NTT energy at 5–7 ms (J mm^{-1})	SD (J mm^{-1})
EVA	10	Dry	4.730 (5 ms)	0.270
	10	Wet (DI H_2O)	4.816 (5 ms)	0.401
	10	Saliva	5.628 (5 ms)	0.492
Pro-form™	10	Dry	3.550 (5 ms)	0.253
	10	Wet (DI H_2O)	3.781 (5 ms)	0.329
	10	Saliva	4.008 (5 ms)	0.543
PolyShok™	10	Dry	6.316 (7 ms)	0.237
	10	Wet (DI H_2O)	5.867 (7 ms)	0.376
	10	Saliva	6.368 (7 ms)	0.551

event was considered to be the time interval during which the impact energy absorption for the test specimen reached this constant level. For EVA and Pro-form™, energy absorption leveled off within approximately 5 ms. The energy absorption for PolyShok™, however, did not reach a constant level until about 7 ms. The horizontal axes in Figs 1–3 have been terminated at these respective time periods, as indicated by the vertical lines with diamond symbols at the top and bottom.

Table 1 summarizes the results for total impact energy absorption, measured after approximately 5 ms (EVA and Pro-form™) or 7 ms (PolyShok™). The energy absorption values were normalized to the thickness (NTT) of the individual specimens for each mouthguard material tested in each condition (dry, wet, and artificial saliva at 37°C) and an impact speed of 20 mph, using 3.0-inch diameter top and 1.5-inch diameter bottom support rings. The NTT energy absorption values (mean ± SD in J mm^{-1} for $n = 10$ replicate specimens in each group were: (i) Dry: EVA 4.73 ± 0.27, Pro-form™ 3.55 ± 0.25, and PolyShok™ 6.32 ± 0.24; (ii) DI water: EVA 4.82 ± 0.40, Pro-form™ 3.78 ± 0.33, and PolyShok™ 5.87 ± 0.38; (iii) Artificial saliva: EVA 5.63 ± 0.49, Pro-form™ 4.01 ± 0.54, and PolyShok™ 6.37 ± 0.55. The small values of the standard deviations show that the impact test results were highly reproducible.

Statistical comparisons were made between the different materials and environments, using two-way ANOVA and the Tukey test. With three materials and three conditioning environments, the number of comparisons was high. Table 2 lists the results of ANOVA and the Tukey test, with adjusted P values in the right column. Each of the first three rows summarizes the result for comparisons of all specimens of the three materials in the two environments shown. All results (*) with an adjusted P value < 0.05 were considered significant.

The first three rows in Table 2 show a comparison among the three conditioning environments, in which the results for all the mouthguard materials have been combined. It can be seen that there was no significant difference for the three mean values of energy absorption for each material when conditioned in air or deionized water. The remaining rows present the results for all pairwise comparisons among the materials and conditioning environments.

Extensive SEM observations failed to reveal definitive differences for each mouthguard material when comparing impact sites for specimens conditioned in any of the environments (dry, water, and artificial saliva). Fig. 4 shows an impacted EVA specimen that had been conditioned in a dry environment. Relatively flat terraced regions are evident, with some wrinkling of the polymer surface. Fig. 5 shows an impacted Pro-form™ specimen that had been conditioned in deionized water, and Fig. 6 shows an impacted PolyShok™ specimen that had been conditioned in artificial saliva. Both Pro-form™ and PolyShok™ exhibited tearing as a major feature of impact fracture, along with fine-scale wrinkling of the polymer surface. Small particles in the PolyShok™ fracture surface are assumed to be polyurethane, and the association of several particles with localized features of the fracture surface is evident.

Discussion

Because of the impossibility in carrying out studies in a true clinical situation, impact testing of mouthguards and mouthguard materials must be performed *in vitro*. In order to compare mouthguard materials under more clinically relevant conditions, Mendel et al. (26) previously conducted impact tests in which specimens were conditioned in deionized water, and results indicated that there may be differences in energy absorption due to the water conditioning. The present study examined further possible environmental differences that an artificial saliva might have on the impact resistance of the mouthguard materials, and included a third group of test samples that were conditioned in this medium. Admittedly, the sample groups for the deionized water and artificial saliva groups were only conditioned for 1 h in these media, but this time period was considered to relevant to typical use conditions by athletes following a period of mouthguard storage at dry (ambient) conditions. While the artificial saliva medium was chosen to simulate the oral environment, we recognize that the more complex composition of oral saliva and presence of oral bacteria are confounding factors that require further study.

Consideration of two other previous studies by Mendel et al. (24, 25), using the same protocol and mouthguard materials, suggest that impact test performance could vary substantially between different batches of the same material. In the present study each mouthguard material was verified by each manufacturer as belonging to the same batch, to avoid any interbatch variation from affecting the results. As previously noted, Table 1 shows that each data set were very uniform with small standard deviations. Thus, there were no evident intra-material differences within each product batch.

The impact speeds of objects that contribute to sports injuries can vary significantly and be well in excess of 60 mph. The upper limit of 20 mph utilized with the present impact-testing protocol was set by the inability of

Table 2. Summary of statistical comparisons for the impact energy absorption of the three mouthguard materials in the three conditioning environments

Material	Environment	vs	Material	Environment	Pr > [t]	Adjusted *P*
	Dry			DI H_2O	0.6530	0.894
	Dry			Saliva	<0.0001	<0.0001*
	DI H_2O			Saliva	<0.0001	<0.0001*
EVA	Dry		EVA	H_2O	0.6132	0.9999
EVA	Dry		EVA	Saliva	<0.0001	<0.0001*
EVA	Dry		PRO	Dry	<0.0001	<0.0001*
EVA	Dry		PRO	DI H_2O	<0.0001	<0.0001*
EVA	Dry		PRO	Saliva	<0.0001	0.0018*
EVA	Dry		POL	Dry	<0.0001	<0.0001*
EVA	Dry		POL	DI H_2O	<0.0001	<0.0001*
EVA	Dry		POL	Saliva	<0.0001	<0.0001*
EVA	DI H_2O		EVA	Saliva	<0.0001	0.0003*
EVA	DI H_2O		PRO	Dry	<0.0001	<0.0001*
EVA	DI H_2O		PRO	DI H_2O	<0.0001	<0.0001*
EVA	DI H_2O		PRO	Saliva	<0.0001	0.0003*
EVA	DI H_2O		POL	Dry	<0.0001	<0.0001*
EVA	DI H_2O		POL	DI H_2O	<0.0001	<0.0001*
EVA	DI H_2O		POL	Saliva	<0.0001	<0.0001*
EVA	Saliva		PRO	Dry	<0.0001	<0.0001*
EVA	Saliva		PRO	DI H_2O	<0.0001	<0.0001*
EVA	Saliva		PRO	Saliva	<0.0001	<0.0001*
EVA	Saliva		POL	Dry	0.0001	0.0036*
EVA	Saliva		POL	DI H_2O	0.1636	0.8924
EVA	Saliva		POL	Saliva	<0.0001	0.0012*
PRO	Dry		PRO	DI H_2O	0.1796	0.9114
PRO	Dry		PRO	Saliva	0.0086	0.0174*
PRO	Dry		POL	Dry	<0.0001	<0.0001*
PRO	Dry		POL	DI H_2O	<0.0001	<0.0001*
PRO	Dry		POL	Saliva	<0.0001	<0.0001*
PRO	DI H_2O		PRO	Saliva	0.1847	0.9167
PRO	DI H_2O		POL	Dry	<0.0001	<0.0001*
PRO	DI H_2O		POL	DI H_2O	<0.0001	<0.0001*
PRO	DI H_2O		POL	Saliva	<0.0001	<0.0001*
PRO	Saliva		POL	Dry	<0.0001	<0.0001*
PRO	Saliva		POL	DI H_2O	<0.0001	<0.0001*
PRO	Saliva		POL	Saliva	<0.0001	<0.0001*
POL	Dry		POL	DI H_2O	0.0099	0.1857
POL	Dry		POL	Saliva	0.7599	1.000
POL	DI H_2O		POL	Saliva	0.0042	0.0922

*All results with an adjusted *P* value < 0.05 were considered significant.

the mechanical testing machine to withstand higher speeds of the striker. The methodology for the present investigation was modified from that in our previous publication (26) by careful attention to placement of the stop blocks that terminated the impact event and by limiting the area of the force-displacement curve for calculation of impact energy absorption to the appropriate time period for the impact event in each mouthguard material. While the present methodology provides an excellent standardized procedure to evaluate the impact properties of mouthguard materials, further research to develop an optimum test protocol simulating clinical conditions is warranted.

For our previous (26) impact tests in dry and wet environments, the energy absorption of PolyShok™ was observed to be significantly greater than that for EVA and Pro-form™. In the present study, PolyShok™ again had significantly higher impact energy absorption than EVA and Pro-form™, regardless of the conditioning procedure. This is particularly important because conditions of clinical application are not always the same. The present results suggest that PolyShok™ will perform the same whether the impact happens when the athlete initially puts in the mouthguard or after it has conditioned in the mouth for a period of time. Table 2 shows that EVA and Pro-form™ absorbed significantly more impact energy after saliva conditioning than when tested in the dry condition. In preliminary experiments with a limited number of specimens, no difference in weight was observed before and after conditioning of the mouthguard materials in artificial saliva, suggesting that bulk absorption did not occur. A future study with a suitable sample size is necessary to investigate the depth of saliva absorption in these materials as a function of time. The present results for EVA are in agreement with those of Coto et al. (9), who found that mechanical properties for EVA improved after conditioning in artificial saliva. In contrast, the present study (Table 2)

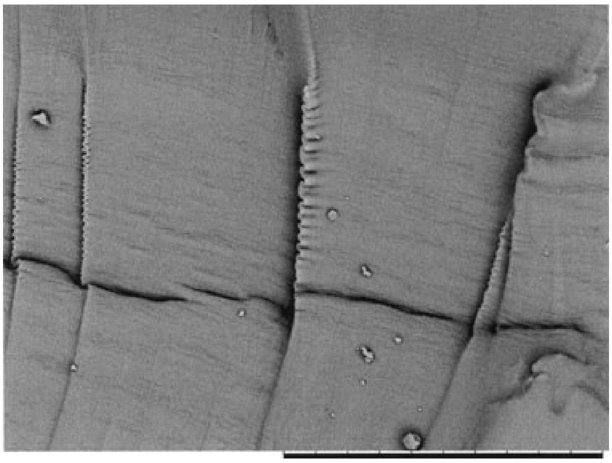

Fig. 4. SEM image near impact site of EVA sample after conditioning 1 h at 37°C in dry environment and loading at 20 mph and 37°C (×1000 original magnification and scale bar length = 100 μm).

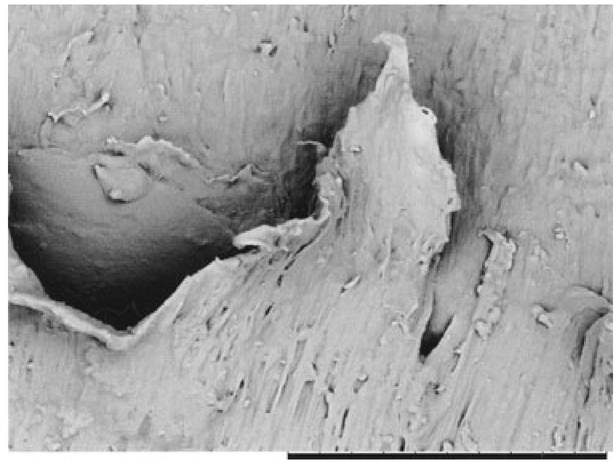

Fig. 6. SEM image near impact site of PolyShok™ sample after conditioning 1 h at 37°C in artificial saliva and loading at 20 mph and 37°C (×1000 original magnification and scale bar length = 100 μm).

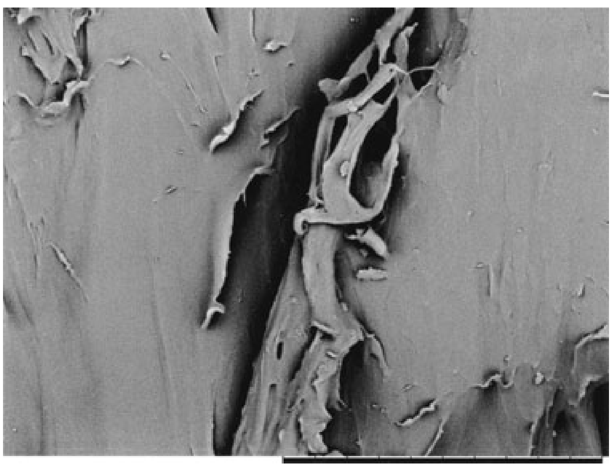

Fig. 5. SEM image near impact site of Pro-form™ sample after conditioning 1 h at 37°C in deionized water and loading at 20 mph and 37°C (×1000 original magnification and scale bar length = 100 μm).

indicated that there was no significant difference in impact energy absorption of PolyShok™ with the three conditioning media.

All three mouthguard materials appeared to be characterized by localized tearing and wrinkling of the surface from the impact loading. These features are expected to be correlated with the fine-scale polymer microstructure, but further study is required to provide details. The superior impact energy absorption of PolyShok™ is assumed to be due in large part to the polyurethane filler particle additives. The association of numerous features on the impact fracture surfaces of PolyShok™ specimens with these particles was noteworthy and similar to that reported in our previous study (27). The absence of major differences in the impact fracture surfaces for each material with the three conditioning media suggests that their effects on the polymer structure are largely at the molecular level and not directly detectable with the SEM.

In addition to its greater ability to absorb energy, PolyShok™ has an additional valuable property compared to EVA and Pro-form™. PolyShok™ sheets have the unique ability of self-lamination using vacuum-formed pressure, instead of requiring expensive high heat and pressure machines. This capability provides three distinct advantages: (i) it allows custom mouthguards to be fabricated in general dental offices, since vacuum-forming equipment is typically available, (ii) It is easy to compensate for loss of individual sheet thickness from processing by combining multiple sheets to obtain a mouthguard of the desired thickness and (iii) It allows individual customization in appearance as decorative items can be placed on the first layer and covered by a second clear laminated top layer. By improving the mouthguard appearance, compliance is increased, especially in younger athletes.

Conclusions

When impacted at 20 mph and 37°C using ASTM Standard D 3763 methodology, PolyShok™ was the most energy-absorbent material in all three conditioning environments, most likely due to its polyurethane additive. EVA was also significantly more impact resistant than Pro-form™ in all three environments. EVA and Pro-form™ performed significantly better after saliva conditioning than dry or water conditioned, but PolyShok™ did not show any difference in energy absorption when conditioned in any of the three environments. SEM examination indicated that the impact failure mode involved substantial wrinkling and tearing of the polymer surface for all three mouthguard materials, and major differences in the failure processes of each material caused by the three conditioning media were not observed. The association of fine-scale fracture surface features with the polyurethane particles in

PolyShok^{TM} was evident, suggesting their important role in the impact energy absorption process.

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