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Impact energy absorption of three mouthguard materials in an aqueous environment

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Abstract – High impact energy absorption is an essential property for mouthguard materials. The impact test performance of three popular mouthguard materials was evaluated, using the procedure in American Society for Testing and Materials (ASTM) Standard D3763. Conventional ethylene vinyl acetate (EVA; T&S Dental and Plastics, Myerstown, PA, USA) served as the control. Pro-form^{TM} (Dental Resources Inc., Delano, MN, USA), another EVA material, and PolyShok^{TM} (Sportsguard Laboratories, Kent, OH, USA), an EVA product containing polyurethane were also evaluated. Specimens having dimensions of 3 inch × 3 inch × 4 mm were prepared from each material. After processing that followed manufacturer recommendations, specimens were conditioned for 1 h in 37°C deionized water and loaded at 20 mph by a 0.5 inch diameter indenter containing a force transducer (Dynatup Model 9250 HV; Instron Corp., Canton, MA, USA). Both large-diameter (3 inches) and small-diameter (1.5 inch) support rings were used. For comparison, two specimens of each material were tested in the dry condition. Energy absorption was determined from the area under the force–time curve at 30 ms, and results for the water-conditioned specimens were compared using ANOVA and the Kruskal–Wallis test. For the large-diameter support ring, energy absorption (mean ± SD in ft·lbf inch^{-1}), normalized to specimen thickness, was: EVA (n = 5), 110.2 ± 48.4; Pro-form^{TM} (n = 4), 110.0 ± 11.3; PolyShok^{TM} (n = 5), 105.7 ± 16.5. For the small-diameter support ring, energy absorption was: EVA (n = 6), 140.5 ± 13.9; Pro-form^{TM} (n = 5), 109.0 ± 26.0; PolyShok^{TM} (n = 6), 124.4 ± 28.4 (1 ft·lbf inch^{-1} = 0.534 J cm^{-1}). Because of substantial variation within some specimen groups, there was no significant difference in energy absorption for the three water-conditioned mouthguard materials and the two support ring sizes. The energy absorption for each material was much greater for other specimens tested in the dry condition.

In recent years, the recognition of the need for mouthguards in the world of sports has increased. Athletes, coaches and parents have joined the dental profession in recognizing the important role a mouthguard plays in the prevention of oral injuries due to trauma. Studies have repeatedly shown that mouthguards reduce the likelihood of dental trauma and brain injury from impact force (1–9). For decades the American Dental Association has advocated the use of mouthguards when there is risk of dental trauma (10). The American Academy of Pediatric Dentistry also advocates the use of mouthguards for prevention of sports-related orofacial injuries (11). It has been long recognized that an essential property of these appliances is high impact energy absorption to prevent transmission of excessive force to the dentition (1, 12).

Mouthguards traditionally have been formulated from ethylene vinyl acetate (EVA) materials (13–26) either as 'boil and bite' or custom-fabricated appliances. Advances in sports dentistry have led to laminates and other innovative strategies to improve energy absorption. The optimum mouthguard thickness (typically about 4 mm) is another important factor, balancing the critical need for energy absorption with patient comfort. Silicone polymers have also been used for mouthguards (17), and both silicone layers and hard polyvinyl chloride inserts have been employed (18).

A wide variety of laboratory tests have been utilized for mouthguard materials (12–29). Many studies have focused on measurement of transmission of impact forces, energy absorption, or the deflection of simulated dentition with laboratory models, using pendulum-type impact apparatus, force sensors or strain gauges (14–19, 21–29).

The purpose of the present investigation was to evaluate three commercially available mouthguard materials, which have been under consideration for use with varsity sports programs at The Ohio State University. An impact energy test (30) used in the polymer industry was selected to compare the three materials.

Materials and methods

Three mouthguard materials were tested: a conventional EVA (T&S Dental and Plastics, Myerstown, PA, USA), serving as the control; Pro-form^{TM} (Dental Resources

Inc., Delano, MN, USA), another EVA thermoplastic material; and PolyShok™ (Sportsguard Laboratories, Kent, OH, USA), an EVA product containing polyurethane.

Manipulation procedures recommended by the manufacturers were utilized to prepare five test specimens of approximately 3 inch × 3 inch × 4 mm dimensions for each material. The starting thickness of approximately 4 mm for the as-manufactured materials was decreased during the processing used to prepare the test specimens. Before the impact testing, these specimens were conditioned for 1 h in 37°C deionized water, removed from the conditioning medium, placed in a test chamber at 37°C, and loaded at 20 mph (miles per hour) by a 0.5-inch diameter indenter containing a force transducer (Dynatup Model 9250 HV; Instron Corp., Canton, MA, USA). For comparison, two specimens of each material from the same batch were also tested in the dry condition. The bottom-support ring for these two groups of specimens had a diameter of approximately 1.5 inch, and the top-support ring had a diameter of approximately 3 inches. Additional specimens were tested (n = 6 for each material) in the wet condition, using a smaller diameter of approximately 1.5 inch for the top-support ring as in our preliminary studies (31, 32). The impact-testing protocol was based upon ASTM Standard D3763 (30). Energy absorption (measured in units of [foot × pounds-force or ft·lbf]) was determined from the area under the force–time curve at 30 ms, using the speed of the impacting indenter (striker) that contained the transducer. Each value of energy absorption was normalized to the measured thickness (NTT) of the specific test specimen. Results for the water-conditioned specimens were compared using ANOVA and the Kruskal–Wallis test.

Results

Figures 1–3 present impact results at 20 mph for the water-conditioned specimens of conventional EVA, Pro-

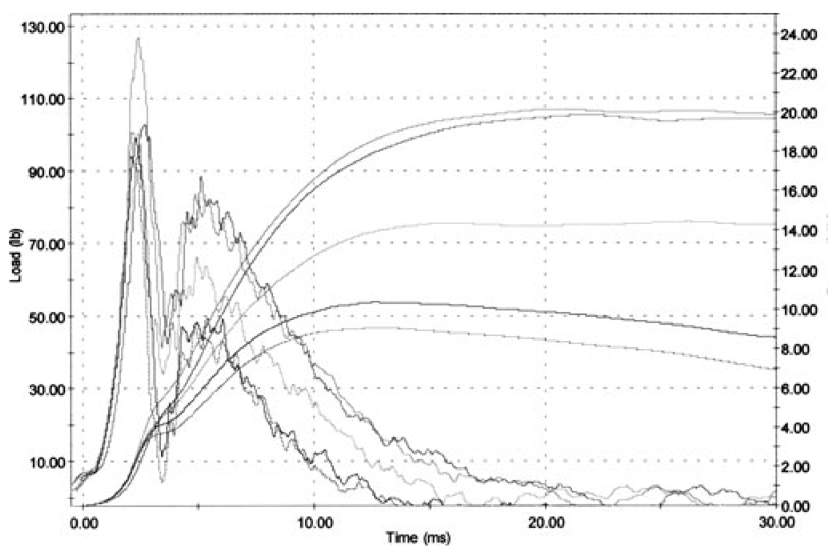

Fig. 1. Impact test results at 20 mph for conventional EVA specimens that had been conditioned for 1 h in deionized water at 37°C and then tested at 37°C. Tests were performed with larger 3-inch diameter top-support ring. No specimens punctured. (In Figs 1–3, the conversion between English and metric units for impact energy is 1 ft·lbf = 1.356 J.)

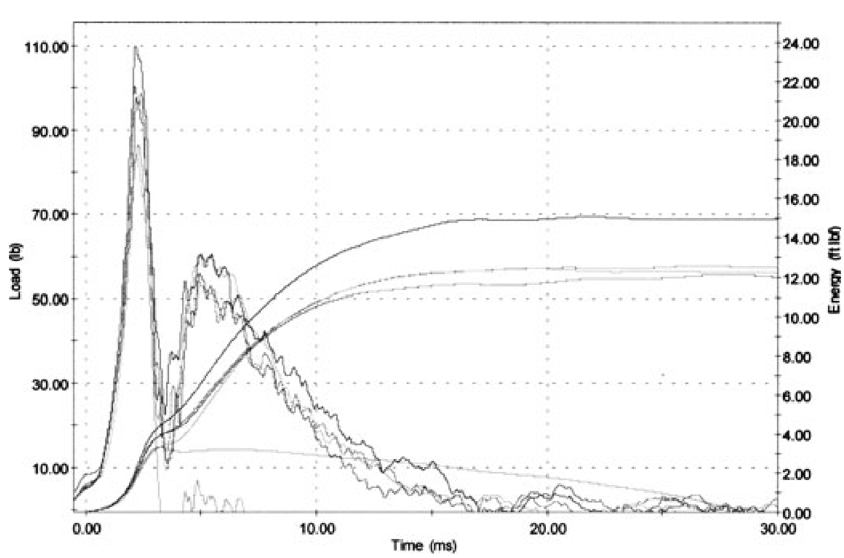

Fig. 2. Impact test results at 20 mph for Pro-form™ specimens that had been conditioned for 1 h in deionized water at 37°C and then tested at 37°C. Tests were performed with larger 3-inch diameter top-support ring. One specimen punctured (bottom plot near 5 ms) and the remaining specimens did not puncture.

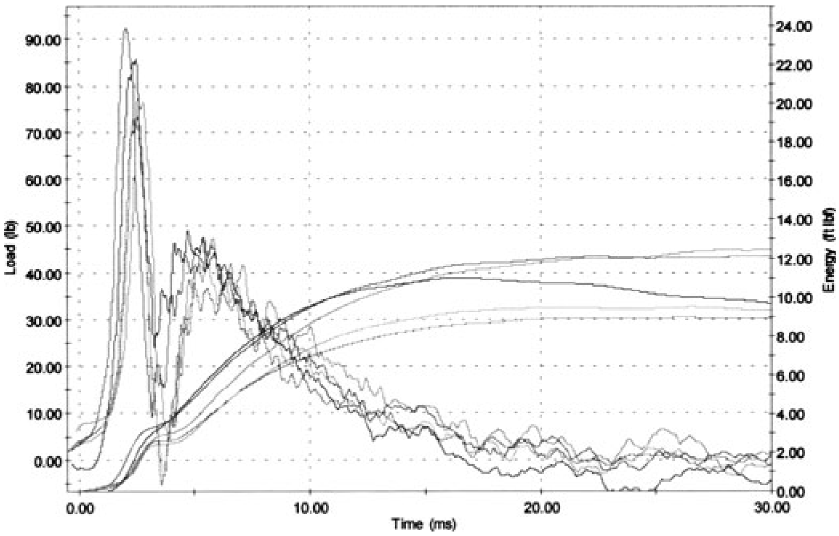

Fig. 3. Impact test results at 20 mph for PolyShok™ specimens that had been conditioned for 1 h in deionized water at 37°C and then tested at 37°C. Tests were performed with larger 3-inch diameter top-support ring. No specimens punctured.

form™ and PolyShok™, respectively, using the larger 3-inch diameter top-support ring. The left vertical axis provides the load (units of lb) sensed by the transducer as a function of time in milliseconds on the horizontal axis. These plots show that the load decreases with time during the impact event. The right vertical axis provides the resulting energy absorption (units of ft·lbf), obtained from integration of the load–time curve, and these plots show the increase in energy absorption during the impact event.

The impact energy absorption for the mouthguard materials typically reached a constant level within approximately 30 ms, and the horizontal axes in Figs 1–3 have been terminated at this time period. There were no punctures for any water-conditioned specimens of conventional EVA and PolyShok™ tested at 37°C and an impact speed of 20 mph, using the 3-inch diameter top-support ring. One Pro-form™ specimen punctured with minimal energy absorption (light blue plot in Fig. 2); the other four Pro-form™ specimens did not puncture.

Table 1 summarizes the total energy absorption at 30 ms, normalized to specimen thickness (NTT), for the three mouthguard materials tested in the wet condition at 37°C and impact speed of 20 mph, using the larger 3-inch diameter top-support ring. The NTT energy absorption (mean ± SD in ft·lbf inch^{-1}) was: EVA (n = 5), 110.2 ± 48.4; Pro-form™ (n = 4), 110.0 ± 11.3; PolyShok™ (n = 5), 105.7 ± 16.5. (The conversion factor to metric units for the NTT energy absorption values is 1 ft·lbf inch^{-1} = 0.534 J cm^{-1}.) The Pro-form™ specimen that punctured with minimal energy absorption was excluded because the impact site was near the manufacturer label. Statistical comparison showed that there was no significant difference in the energy absorption for the three mouthguard materials.

Table 2 summarizes the total energy absorption at 30 ms, normalized to specimen thickness (NTT), for the three mouthguard materials tested in the wet condition at 37°C at an impact speed of 20 mph, using the smaller 1.5-inch diameter top-support ring. The NTT energy absorption (mean ± SD in ft·lbf inch^{-1}) was: EVA (n = 6), 140.5 ± 13.9; Pro-form™ (n = 5), 109.0 ± 26.0; PolyShok™ (n = 6), 124.4 ± 28.4. The sixth Pro-form™ specimen punctured during testing and was excluded from the calculations.

Table 1. Results for total energy at 30 ms, normalized to thickness (NTT), for the three mouthguard materials tested in the wet condition at 37°C at an impact speed of 20 mph, using the larger 3-inch diameter top-support ring. Before testing, specimens were conditioned for 1 h in 37°C deionized water. One Pro-form™ specimen that punctured with essentially zero NTT energy (Fig. 2) at 30 ms was excluded from calculations of mean and SD. There were no punctures for other specimens in this table (For Tables 1–4, 1 ft·lbf inch^{-1} = 0.534 J cm^{-1}.)

Mouthguard material	Specimen number	NTT energy at 30 ms (ft·lbf inch^{-1})
EVA	1	55.56
	2	110.85
	3	158.02
	4	158.47
	5	68.32
Mean		110.24
SD		48.36
Pro-form™	1	110.97
	2	101.92
	3	101.53
	4	125.63
Mean		110.01
SD		11.29
PolyShok™	1	92.71
	2	91.98
	3	111.98
	4	131.41
	5	100.52
Mean		105.72
SD		16.47

EVA, ethylene vinyl acetate.

Due to the large differences in variances, the results in Tables 1 and 2 were compared statistically using the Kruskal–Wallis test. No significant differences were found between any of the groups across both tables.

Table 2. Results for total energy normalized to thickness (NTT) at 30 ms for the three mouthguard materials tested at 37°C in the wet condition at an impact speed of 20 mph, using the smaller 1.5-inch diameter top-support ring. Before testing, specimens were conditioned 1 h in 37°C deionized water. A sixth Pro-form™ specimen punctured and was excluded from calculations of mean and SD. None of the other specimens punctured

Mouthguard material	Specimen number	NTT energy at 30 ms (ft·lbf inch^{-1})
EVA	1	158.15
	2	156.30
	3	138.31
	4	123.28
	5	131.97
	6	135.07
Mean		140.51
SD		13.89
Pro-form™	1	107.75
	2	126.05
	3	139.45
	4	100.08
	5	71.61
Mean		108.99
SD		25.97
PolyShok™	1	91.04
	2	138.95
	3	130.41
	4	102.63
	5	113.60
	6	169.87
Mean		124.42
SD		28.35

EVA, ethylene vinyl acetate.

Table 3. Results for total energy, normalized to thickness (NTT), at 30 ms for two specimens of each mouthguard material tested in the dry condition at 37°C and an impact speed of 20 mph. The larger 3-inch diameter top-support ring was used

Mouthguard material	Specimen number	NTT energy at 30 ms (ft·lbf inch^{-1})
EVA	1	140.70
	2	178.21
Mean		159.45
Pro-form™	1	143.95
	2	126.29
Mean		135.12
PolyShok™	1	118.98
	2[1]	168.40
Mean		143.69

EVA, ethylene vinyl acetate.
[1]Specimen was impacted twice, and data were recorded after second impact.

Table 3 presents the results for total energy absorption at 30 ms, normalized to specimen thickness (NTT), for two specimens of each mouthguard material, tested in the dry condition at 37°C and an impact speed of 20 mph. The larger 3-inch diameter top-support ring was used. For the two specimens, the mean NTT energy absorption (ft·lbf inch^{-1}) was: EVA, 159.4; Pro-form™, 135.1; and PolyShok™, 143.7. Comparing Table 3 and Table 1, it can be seen that the impact energy absorption of the three mouthguard materials tested at 37°C and 20 mph decreased considerably when these materials were conditioned in deionized water. Because of this evident effect, two specimens of each mouthguard material were deemed sufficient to demonstrate the much greater impact energy absorption for the dry condition, which has no clinical relevance.

Table 4. Summary of previous preliminary results (32) for total energy, normalized to thickness (NTT), for the three mouthguard materials tested in the dry condition at 37°C at an impact speed of 20 mph. The smaller 1.5-inch diameter top-support ring was used. All of the conventional EVA and Pro-form™ specimens punctured, whereas none of the PolyShok™ specimens punctured

Mouthguard material	Specimen number	NTT energy at 30 ms (ft·lbf inch^{-1})
EVA	1	141.80
	2	74.65
	3	70.57
	4	169.04
	5	63.26
Mean		103.86
SD		48.21
Pro-form™	1	53.56
	2	47.50
	3	55.90
	4	55.46
	5	64.14
Mean		55.31
SD		5.97
PolyShok™	1	187.45
	2	191.22
	3	186.06
	4	185.26
	5	209.79
Mean		191.96
SD		10.22

EVA, ethylene vinyl acetate.

Discussion

Table 4 presents results from our previous preliminary study (32) for the total energy absorption at 30 ms, normalized to specimen thickness (NTT), for the three mouthguard materials tested at 37°C in the dry condition at an impact speed of 20 mph, using the smaller 1.5-inch diameter top-support ring. All of the conventional EVA and Pro-form™ test specimens punctured during impact loading, whereas none of the PolyShok™ test specimens punctured. In addition, the impact energy absorption for PolyShok™ was significantly greater than that for conventional EVA and Pro-form™ when the impact specimens were tested in the dry condition.

Results from the present impact tests at 20 mph with the mouthguard materials in the wet condition (Table 2) and from our preliminary study (32) at the same impact test speed with the mouthguard materials in the dry condition (Table 4), using the same 1.5-inch diameter top-support, suggest that impact test performance can vary substantially between batches of the same mouthguard material. It is tempting from comparison of Tables 1 and 2 to suggest that impact energy absorption is generally greater (conventional EVA and PolyShok^{TM}) for the smaller diameter top-support. However, this conclusion is not supported by statistical analysis across all three materials and the two top-support diameters. The absence of significance when the data in Tables 1 and 2 were compared statistically was strongly influenced by the very large standard deviation for the EVA group in Table 1 and does not preclude the existence of actual differences between some groups of test specimens in these two tables.

A substantially larger sample size in each specimen group for future impact tests would be needed for a definitive conclusion about the effect of top-support diameter. Use of the smaller-diameter top-support ring concentrates the impact loading on the test specimen, whereas use of the larger-diameter ring allows the specimen to undergo greater flexure to withstand the impact loading during the test event. In future testing all specimens of each mouthguard material should be prepared from the same manufacturer batch of each product.

The considerable decrease in impact energy absorption on going from the dry condition (Table 4) to the wet condition (Table 1) for all three mouthguard materials can be attributed to degradation of the polymer matrix by water, which has been described for dental resin composites (33). While precise simulation of clinical use conditions for the mouthguard materials is difficult, it was considered that conditioning for 1 h in 37°C deionized water before testing would be a reasonable approach to clinical use conditions for the mouthguard materials in the present laboratory study. Because artificial saliva compositions contain constituents having larger molecular sizes, which would have greater difficulty diffusing into the polymeric mouthguard materials, this environment may be less aggressive than deionized water and will be utilized as a conditioning medium for future study. A critical indicator of the importance of water-conditioning the test specimens was the previous finding (32) that all conventional EVA and Pro-form^{TM} test specimens punctured at the 20 mph impact test speed when the dry condition at 37°C was used (32), whereas puncture at 20 mph occurred for only one Pro-form^{TM} specimen when the three mouthguard materials were water-conditioned before testing at 37°C. Puncture occurred near the manufacturer label on this specimen, suggesting that such labeling should be located on mouthguards at sites that are remote from likely impacts during their use.

Insight into potential fundamental mechanisms at the microstructural level for energy absorption by these mouthguard materials has been gained by scanning electron microscope (SEM) observations (34) of impact test specimens in the dry condition from the preliminary study at 20 mph speed (32). Conventional EVA surfaces appeared to be stretched with parallel fissures; Pro-form^{TM} surfaces contained transverse wrinkled patterns within parallel curvilinear features; and PolyShok^{TM} surfaces had numerous porous areas adjacent to nodules, suggesting that the EVA polymer matrix had detached from polyurethane filler particles (34). Further SEM study of specimens tested in the wet condition is necessary to ascertain whether the same microstructural mechanisms for impact energy absorption appear to be operative.

The ASTM test protocol for polymer energy absorption (30) appears to be a worthwhile methodology for evaluation of mouthguard materials, provided the impact test specimens receive conditioning that is appropriate to clinical use. However, the present results must be interpreted with caution because test specimens were not supported by teeth or an equivalent structure, as in some previously reported studies of mouthguard materials (18, 25–27, 29). Recent research by Takeda et al. (24, 28) and Walilko et al. (29) demonstrate the importance of the impacting object and sensor type, as well as test methodology in general.

In conclusion, it is important to note that, besides energy absorption, another important consideration for selection of a mouthguard material is the ease of forming a laminated structure (35, 36), which is an advantageous feature of PolyShok^{TM} compared with EVA and Pro-form^{TM}. Also critical is acceptance of the mouthguard by the athlete, which is often related to the fit and comfort of the appliance. The most superior mouthguard in terms of energy absorption and other clinically relevant physical properties is of no benefit if it is not worn by the athlete.

Conclusions

Impact testing at 20 mph of conventional EVA, Pro-form^{TM} and PolyShok^{TM}, using methodology based upon ASTM Standard D 3763, revealed no significant difference in energy absorption or puncture resistance, when these materials were conditioned for 1 h in deionized water at 37°C before testing at body temperature. No significant difference in energy absorption was observed with the use of small-diameter (1.5 inch) or large-diameter (3 inch) top-support rings. Substantial variation in impact behavior was found within sample groups, in particular the occurrence of low energy absorption and puncture when the impact site was near the manufacturer label on a test specimen. Comparison of present test results with previous preliminary results for specimens tested in air without prior water conditioning suggests that the impact resistance behavior for these mouthguard materials might vary with different manufacturer batches of the same product.

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