ORIGINAL ARTICLE

Effect of ethylene vinyl acetate (EVA) closed cell foam on transmitted forces in mouthguard material

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Objectives: To compare transmitted forces through ethylene vinyl acetate (EVA) mouthguard material and the same EVA material with gas inclusions in the form of a closed cell foam.
Method: EVA mouthguard materials with and without foam gas inclusions and 4 mm thick were impacted with a constant force from an impact pendulum. Various porosity levels in the foam materials were produced by 1%, 5%, and 10% by weight foaming agent. The forces transmitted through the EVA after energy absorption by the test materials were measured with a force sensor and compared.
Results: Only minor non-significant differences in transmitted forces through the EVA with and without foam were shown.
Conclusions: The inclusion of gas in the form of a closed cell foam in 4 mm thick EVA mouthguard materials did not improve the impact performance of the EVA mouthguard material.

Energy absorption is an important characteristic of mouthguards worn to reduce injuries to the orofacial complex in contact sports.[1–3] Mouthguards reduce impact forces to teeth and jaws as well as reduce lacerations to soft tissues. Concussion is also claimed to be reduced in contact sports in those wearing mouthguards.[4]

Better performance of mouthguards through improved energy absorption and reduction in transmitted forces can be observed when mouthguards are thicker[5–8] or when there are air inclusions in the mouthguard material.[9] However, thicker mouthguards result in impaired speech and reduced respiratory efficiency.[10] Air inclusions have been shown to improve energy absorption, reduce transmitted forces, and eliminate rebound within impacts with no corresponding increase in the thickness of the mouthguard.[11] Similar improvements in energy absorption from impacts have been shown with modern athletic shoes and "bubble wrap" packaging of fragile goods, both of which have air or gas inclusions in their construction.

Mouthguards are usually manufactured from the ethylene vinyl acetate (EVA) polymer. It seems logical that foams with gas inclusions in an EVA polymer would aid energy absorption if used in the construction of sporting mouthguards. Foams are different, however, from the air inclusions described by Westerman *et al*,[9] where air cells were formed in mouthguard materials with regular patterns and specific air cell volumes and wall thickness. With a foam material, gas cells are formed in an indiscriminate manner within the polymer.

Another obvious advantage of an EVA foam would be a reduction in the weight of the polymer in a mouthguard, which could lead to savings in manufacturing costs by reducing the amount of raw material used. Questions could arise, however, about the "mouldability", durability, finishing requirements, and the consequent problems with oral bacteria if the foam inclusions of the mouthguard are breached. Most important, however, is whether foamed EVA would provide improved performance in mouthguards through greater energy absorption and reduced transmitted forces from impacts capable of breaking teeth.

The aim of this study was to compare the transmitted forces through EVA mouthguard materials with gas inclusions formed by the closed cell foaming process, with the same EVA polymer of the same thickness but without foam.

MATERIALS AND METHODS

Test samples were obtained by injection moulding EVA polymer with a foaming agent into a die, which produced samples with dimensions of 100 mm × 100 mm and 4 mm thick. Samples of the control material with the same dimensions but without foaming agent were also made. All of the materials were made from the same EVA polymer (Elvax, DuPont, Melbourne, Australia) with a Shore A Hardness of 83, and the foaming agent Hydrocerol (Boehringer, Ingleheim, Germany) was used. Hydrocerol was added to the EVA in 1%, 5%, and 10% by weight concentrations, and the test samples were manufactured by INZTEP Pty Ltd, Wanganui, New Zealand.

Test samples and the control material were then subjected to the same impact force by using a pendulum apparatus similar to an Izod or Charpy impact tester (Australian Standard 1544, 1989), which produced constant impacts of 4.4 J of energy and a velocity of 3 m/s. The impact head was flat and circular with a 12.5 mm diameter, and each test material sample was impacted five times but once only at each impact site. Four samples of each material were prepared, and so a total of 20 impacts were imparted to each of the test materials with foam and the control without foam.

The transmitted forces through the materials were measured using a force sensor (model 208A15; PCB, Depew, New York, USA), and amplified, conditioned (model F484B06; PCB), analysed (model 2200; Diagnostic Instruments, Livingston, Scotland, UK), and stored on a computer. Statistical analysis used Minitab (Minitab Inc, State College, Pennsylvania, USA), and graphical analysis was conducted with Microsoft Excel (Microsoft Corporation, Seattle, Washington, USA). Comparisons between the different materials tested were analysed.

Scanning electron microscopy was used to examine the gas inclusions in the different samples with the different foaming concentrations. A wedge shaped sample was obtained from each EVA disc by slicing with a razor blade, using minimal pressure to reduce distortion of the cut face. These samples were applied to standard size scanning electron microscope specimen stubs using adhesive discs, the distinctive wedge shape allowing quick and unambiguous recognition of all surfaces.

Specimens were placed under a slight vacuum (about 10^{-3} T) in a vacuum evaporator for three hours to minimise outgassing, and then coated with a thin layer of carbon to prevent charge build up under scanning electron microscope observation. They

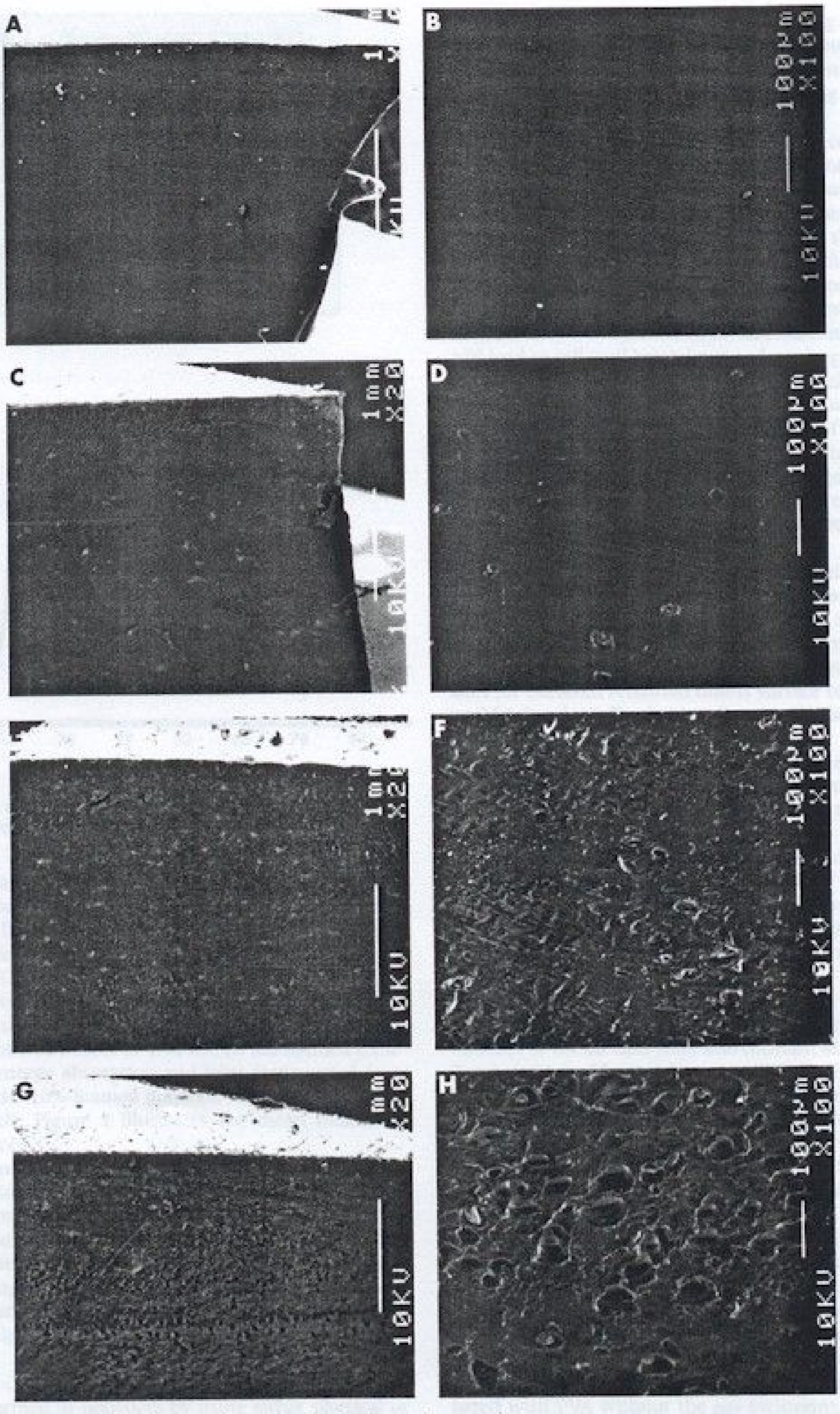

Figure 1 Changes in size and distribution of gas inclusions in the various samples.

were examined with a JEOL 6400 scanning electron microscope operating at an accelerating voltage of 10 kV. Representative photographs were taken at magnifications of × 20 and × 100.

RESULTS

The cut surface of unfoamed EVA material showed a homogeneous texture with little more than fine score marks from the razor's edge as it sectioned through the material. The addition of foaming agent to the EVA polymer mixture resulted in the formation of regular gas porosities (fig 1A, B). EVA material containing 1% foaming agent had occasional inclusions of about 20 µm diameter. However, with increasing concentration of foaming agent, the gas generated porosities became larger and more heterogeneous in size. EVA polymer material containing 10% foaming agent showed this effect the most clearly. The porosities ranged in size from less than100 µm diameter and regular in shape to larger than 1

Table 1 Mean maximum transmitted forces through foamed and non-foamed ethylene vinyl acetate (EVA) mouthguard material

Foaming agent (% weight)	Transmitted forces (kN)	Standard deviation
0.0 (control)	4.04	0.21
1.0	4.12	0.08
5.0	4.08	0.10
10.0	3.88	0.16

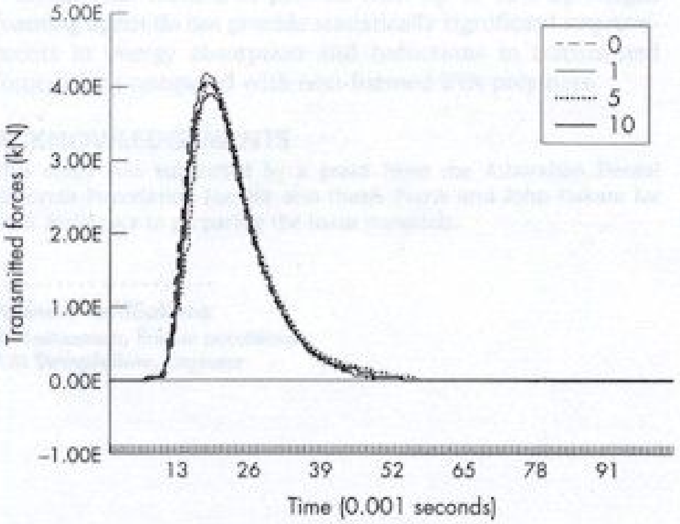

Figure 2 Mean maximum transmitted forces of foamed and non-foamed ethylene vinyl acetate (EVA) mouthguard material.

mm diameter and irregular in shape. The large porosities tended to be located in deeper regions of the disc material about 0.5 mm from the surface, with this region becoming more clearly defined with increasing concentration of the foaming agent (fig 1G, H).

Table 1 shows the various mean maximum transmitted forces through the various materials. The EVA material without foam transmitted a force of 4.04 kN. Of the foamed materials, the best energy absorption and least transmitted force occurred with the 10% foamed polymer, which transmitted a force of 3.88 kN. Figure 2 illustrates the mean maximum transmitted forces.

A one way analysis of variance was completed on the test data. The maximum transmitted force for each set of five impacts per sample was averaged for each test material and the control. Analysis was performed on these averages and no significant differences were found between the tested samples. Although there were small differences between the forces associated with the various levels of foaming, these were not statistically significant.

DISCUSSION

Foam can be formed in polymers by using either physical or chemical foaming agents. The physical production of foam usually involves a change of state such as liquid to gas whereas a chemical foaming agent produces the foaming effect by a chemical reaction. Heat is often important in starting and maintaining the foaming process.

The foaming agents most commonly used in EVA polymers are chemical agents, and the material used in this study was Hydrocerol, a citric acid/sodium bicarbonate material that produces relatively high gas yield at low temperatures (140 °C). The gas produced by the foaming agent is carbon dioxide, and small quantities of water are also formed.

In this study various amounts of foaming agent were added to the EVA polymer during injection moulding of the test samples. The additives were calculated on a percentage by weight basis and ranged from no foaming agent to 10% by weight of agent to EVA polymer.

The formation of a plastic foam polymer can be described in four steps. Firstly, the foaming agent is thoroughly dispersed within the EVA polymer. Secondly, individual gas pockets are formed when the foaming agent is heated during the extrusion/injection moulding process. The third step involves the growth in size of the initial gas cells as more gas is diffused through the polymer. This produces a closed cell foam. If the growth of these individual gas cells continues long enough, the cells will contact each other, and continued gas formation will lead to cell wall breakdown to form larger interconnected cells, which are identified as open cell foams. If the coalescence of gas cells is allowed to continue indefinitely, such as would occur with large additions of foaming agent in a polymer, the foam will collapse. The fourth step involves stabilisation of the foamed polymer when gas cell growth no longer occurs. This is usually achieved by cooling the foamed material. In this study, the foaming process was stopped before the formation of open cell foam.

From a clinical perspective, open cell foams present problems with bacterial contamination. The modification and finishing of mouthguards constructed with such foams, either by cutting or grinding, would result in open voids within the mouthguard material. In the mouth, these open cells are ideal sites for bacterial retention unless surface sealing of the foam could take place. Further studies are planned to identify the impact characteristics of open cell foams.

The impact results from the closed cell foams can be compared with other air inclusions in mouthguard materials. A previous study identified the reduction in transmitted forces through samples made from Stay-guard material (Rudolf Gunz and Co, Sydney, Australia).[9] This commercially available EVA polymer with a Shore A Hardness of 85 and the same thickness of 4 mm showed more than 30% reduction in transmitted force when impacted with a similar force. This compares with a reduction of 4.96% in the transmitted force in this study of closed cell foam.

The earlier study featured air inclusions in which the air cells were all the same dimension throughout the test samples. The volumes of the air cells were also constant at either $8\ mm^3$ ($2 \times 2 \times 2$ mm) or $18\ mm^3$ ($3 \times 3 \times 2$ mm). The wall thickness between air cells was also controlled at either 1 or 2 mm. This contrasts with the closed cell foam where the formation of gas inclusions provided variable cell volume and wall thickness.

There was also a slight difference in the Shore A Hardness of the polymers in the two studies with the different air or gas inclusions: 85 in the earlier study and 83 in this one. It would be expected that the harder material (85) would transmit more force because of its greater hardness and reduced elasticity. However, the transmitted forces through the air inclusion material with fixed air cell volume and wall thickness were reduced by 32% compared with the EVA polymer without air cells. In contrast, closed cell foam EVA polymer showed a 4.96% reduction in transmitted forces compared with EVA without the gas inclusions. The reduction in transmitted forces under the same conditions (magnitude of test impact force, thickness of test samples, and similar air conditioned environment) and with similar EVA polymers showed that the improvements in the foam EVA polymer were only one sixth of those shown with the more controlled air inclusions with regular volume and wall thickness.

Conclusions

The addition of foaming agent to the EVA (Shore A Hardness 83) commonly used in mouthguard materials produced closed cell foams that showed small increases in energy absorption

Take home message

Closed cell, foamed EVA mouthguard material containing up to 10% by weight foaming agent does not significantly improve energy absorption when impacted compared with non-foamed material.

when impacted compared with the same material without foam. Reductions of about 5% in transmitted forces in these foam materials contrasted with a 32% reduction in materials with larger air inclusions and fixed air cell volume and wall thickness.

Closed cell foam EVA plastics with up to 10% by weight foaming agent do not provide statistically significant improvements in energy absorption and reductions in transmitted forces when compared with non-foamed EVA polymers.

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Sporting images

Pelota: a ball game, of Basque origin, resembling fives, using a basket catching and throwing device.