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Evaluating the Performance of Helmet Linings Incorporating Fluid Channels

D. Stewart¹, L. R. Young¹, R. Goel¹, and G. Christou¹

ABSTRACT:

Performance advantages of incorporating fluid channels into foam made of DERTEX² VN600 (Vinyl Nitrile) are evaluated. This foam has the potential to replace the traditional foam material of helmet liners, like Expanded Polystyrene (EPS). Experiments involved dropping a certified size E headform vertically onto a flat, solid anvil. Elastically deformable and resilient VN foam outperformed EPS during all impacts. Incorporating a viscous aqueous solution of 30% by weight Glycerin, into 3/8 in. (0.95 cm) diameter channels, machined through VN foam, reduced the peak headform acceleration by 12% on first impact compared to VN foam samples without fluid channels. The reduction was 17% when compared to EPS foam samples. The duration of first impact increased by 27% over EPS, significantly lowering the associated Head Injury Criterion (HIC) values. Repeated impact testing demonstrated an increasing performance advantage of incorporating fluid channels. Samples incorporating 30% Glycerin solution reduced the peak headform acceleration after six impacts by 50% as compared to EPS.

KEYWORDS: helmet, impact testing, ski injury, vinyl nitrile foam, head injury

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Introduction

Helmets can provide protection to the human head from dangerous impacts occurring in sport, in recreation, in the work place and during combat. Helmets were traditionally designed to prevent potentially catastrophic injuries such as skull fracture and other serious head injuries often associated with long term brain damage and death. Increased awareness of repeated impact effects has caused a change in helmet design, acknowledging that severe concussion can be as harmful as skull fracture in the medium to long term [1]. Although the exact mechanism of concussion is still under study, head accelerations and HIC have been found to correlate well with the likelihood of concussion [2].

The majority of modern ski helmets use Expanded Polystyrene (EPS) foam liners with a thin, hard plastic exo-skeleton to prevent sharp objects penetrating through the liner. The concept is quite simple. Upon impact the EPS foam deforms, absorbing some of the impact and reducing the energy imparted to the head. EPS foam has many advantages including light weight and low expense. However the irreversibility of the foam deformation reduces the helmet's performance for subsequent impacts, eventually providing almost no protection. EPS foam deforms locally at the collision site, leaving the forces concentrated only near the area of impact. As a result, a higher peak pressure force is experienced locally on the skull than if the impact were to be distributed over a larger area.

Head injuries account for a 10-20% of all injuries in snow sports [3]. A Japanese study [4] found that the overall rates for head injury were 6.5 per 100,000 visits for snowboarders and 3.8 for skiers. A case-control study was conducted to determine whether wearing a helmet protected young skiers and boarders against head injury [5]. Head, face and neck injuries in children aged less than 13 years were recorded and it was found that the helmets lead to a 43% reduction in the

risk of head, face and neck injuries. Furthermore, it was found that no serious neck injuries occurred as a result of wearing a helmet.

In a case-control study from Canada [6], 1082 skiers and snowboarders with head or neck injuries were compared with 3295 skiers and snowboarders without head or neck injuries. It was found that wearing a helmet reduced the overall risk of head injury by 29%. Considering those who required ambulance transport, wearing a helmet reduced the risk of head injury by 56%. No associations were found between wearing a helmet and the occurrence of neck injuries. In another case control study from Norway [7] involving 3277 snow sports injuries, the overall incidence of head injury was found to be 17.6%. They found a 53% higher incidence of head injuries amongst snowboarders compared to alpine skiers. Using a helmet reduced the risk of sustaining a head injury by 60%. They also found low incidence of neck injuries amongst those wearing a helmet. In short, there is well established evidence that wearing a helmet reduces head injuries.

The three deformable bodies which absorb energy in a head impact are the head, the object being hit and the helmet lining. It is the purpose of the helmet to attenuate rather than eliminate shock and to manage the impact by deformation. Energy absorbing materials and structures are used in a broad range of everyday applications such as in vehicle protection, ballistic armor, sporting equipment and protective clothing. Polymer foams with microstructures of open and closed cells are the most widely used energy absorbing materials [8].

There have been significant improvements in helmet safety in recent years; however, evidence suggests that further improvement is required. Research into helmet liners incorporating fluids has been conducted at MIT since 2004 [9]. Our previous research showed that a 35% reduction in peak forces imparted to the head can be achieved by using VN foam which is surrounded by high viscosity fluid, compared to just using VN foam. Both the temporal and spatial distribution of

pressure was improved by the addition of fluid filled channels. We further showed the advantage of cutting fluid channels in block samples of 1/2 in. thick VN foam [10].

The purpose of the present study was to extend our earlier studies [9, 10], and to assess the possible advantages of incorporating fluids in 1 in. (2.54 cm) thick VN foam which can replace a conventional helmet liner and can better distribute the energy spatially upon impact. Fluid channels incorporated within the lining deform upon impact, squeezing the fluid away from the contact point. Fluid viscosity, along with foam compression, acts as the principle shock absorption mechanisms, converting the kinetic energy of impact into heat. Once the fluid begins to flow away from the contact point and the duration of impact increases, the net forces become less localized resulting in a lower peak pressure and peak force experienced by the headform. This will reduce the cases of skull fracture and also the likelihood of concussion and hematoma.

Materials and Methods

The drop test assembly closely conformed to the ASTM helmet drop testing standard [11] of a flat, solid anvil, made of steel. An ASTM size E headform was used. ASTM specifications call for the drop height to be 2 m, but some logistical limitations prevented us from replicating the full drop height as per ASTM standard. The height of our drop test assembly is 1.54 m. To compensate for this, additional mass was added to the head form, so that the momentum of the falling element, at impact, was the same as per ASTM drop test standard (31.32 Nm), rather than matching the kinetic energy. In theory, the forces should therefore be identical. ASTM specifications call for total mass of the drop assembly to weigh no more than 5 kg. The weight of our test assembly is 5.7 kg.

Dropping from a lower height of 1.54 m, corresponded to a theoretical impact velocity of 5.5 m/s with 86.2 J of kinetic energy, whereas the 2 m drop height as specified by ASTM, had impact velocity of 6.2 m/s and kinetic energy of 96.1 J. The maximum measured impact velocity of the headform was 5.4 m/s and the average was 5.36 m/s. The kinetic energy at impact was reduced by 10% compared to the ASTM standard.

In all experiments, the headform acceleration during impact was recorded. Accelerometers producing a linear response up to 250 g were connected to a computer using an eight channel data acquisition system (DAQ). INSTACAL software recorded the results every 0.1 millisecond to produce an acceleration plot of the impact. The average peak value of acceleration was calculated using data from two accelerometers in parallel, attached to the headform. Acceleration was measured uni-axially. The guide rails were straight and well greased, visual inspection did not find any off-vertical motion during the drop, hence off axis accelerations are assumed to be negligible.

Two light gates placed vertically 4.25 cm apart along the guide rails near the sample and were used to trigger the data logger. The time duration between passages through two light gates was used to calculate the impact velocity. The theoretical impact velocity was 5.5 m/s. Measurements which were outside the 95% threshold (< 5.225 m/s) were discarded in our analysis.

Accelerometer data was visually inspected to record the time at which the acceleration started rising above the baseline and the time at which it dropped down to base line. Difference of these two time records gave the impact duration.

A total of three individual tests were completed as part of this study, each aimed at further developing the fluid liner technology. Each test contained a number of samples, designed differently to investigate the associated effects on performance. Four to six samples were tested

for each configuration. Each sample was subjected to six repeated drops with a two minute gap between impacts to allow for foam recovery. All samples were prepared at standard room temperature and humidity conditions. Peak acceleration, maximum impact force, impact duration and HIC values were compared between different groups of the same test. No other statistical analysis was performed across different groups of samples.

Tests were performed on flat 3.75 in. x 4.5 in. (9.52 cm x 11.43 cm) sample blocks of 1 in. (2.54 cm) thickness VN foam, weighing 30.67 g. These samples were compared with 1 in. (2.54 cm) thick EPS foam samples of the same dimensions, weighing 16.8 g. Initial experiments tested VN foam without any fluid channels to compare energy absorbing capacity of the foam against a similar thickness EPS liner. The EPS foam replicated that found commonly in ski helmets, with a density of 60.68 kg/m³. VN is closed cell foam with a density of 107 kg/m³. Unlike EPS, it has the ability to absorb repeated impacts with only marginal loss in performance. Six samples of each were used.

Five channel diameters, of 1/8 in. (0.32 cm), 1/4 in. (0.64 cm), 5/16 in. (0.79 cm), 3/8 in. (0.95 cm) and 7/16 in. (1.11 cm) were tested. Each sample contained five channels of equal diameter (Fig. 1), spaced 0.625 in. (1.58 cm) apart. VN foam was tested with both constrained and unconstrained fluid channels (Fig. 2), testing both a compressible fluid (air) and an incompressible fluid (water) at room temperature in the channels. For the constrained samples all the fluid was contained within the channels, whereas for the unconstrained case the ends of the channels were open to reservoirs and the fluid could flow out of the foam. The design of constrained fluid samples anticipated that fluid squeezed away from the area of impact would expand evenly along the length of the channels. The channels would expand into the foam to accommodate the increased local volume, while the energy of the impact would be fully

absorbed by foam compression along the full length of the channels. To seal the ends of the channels, thin strips (1/2 x 1/2 x 3.5 in.) of VN foam were cut and glued to the ends. The unconstrained fluid channel design allowed the displaced fluid from impact to simply flow unimpeded through the channel and out into a reservoir. Energy was absorbed both through viscous effects of fluid motion but also through compression of the surrounding foam. The reservoir system was a method of catching the displaced fluid and then efficiently returning it to the channel after impact. In the case of air, no reservoir system was required. Four identical samples of each arrangement were tested.

In the Fluid Viscosity Test the diameter of the channels was fixed and the effects of fluid viscosity on energy absorbing characteristics were examined using the unconstrained channel design. Mixtures of water and Glycerin were used to test different viscosity fluids in the channels. Glycerin is a colorless, odorless, viscous liquid that is widely used in pharmaceutical formulations and in the food industry as an artificial sweetener. Glycerin can mix with water to form an aqueous Glycerin solution of known viscosity. Five viscosity conditions at 10%, 20%, 30%, 40% and 50% weight Glycerin were tested using six samples each time.

Results and Discussion

EPS versus VN foam Test

Test found a considerable performance advantage offered by VN foam over EPS on a flat, solid anvil (Fig. 3). For the first impact, the average peak acceleration recorded for EPS was 114 g, whereas for VN foam it was 110 g. Even though there was no significant difference for the first impact, performance of VN foam degrades much less than EPS for multiple impacts. Peak acceleration for EPS for the 6th impact was 240 g, whereas for VN foam it was 174 g. For

multiple impacts VN foam outperformed EPS, resulting in a 27% decrease in peak headform acceleration after six impacts. VN foam is denoted as DERTEX foam in the figures. Error bars indicate standard error for six samples.

Channel Diameter Test

Experimental testing explored the possibility of incorporating fluid channels into VN foam samples. The first phase of this test examined constraining the water into the channels. This was found to reduce the energy absorbing capacity of the sample and consequently increased the peak headform acceleration. The reduction in performance was attributed to the foam sample not expanding sufficiently around the fluid channel to accommodate the displaced fluid squeezed away from the point of impact. However, VN foam samples involving unconstrained water channels were found to better absorb the forces of impact than a VN foam sample without fluid channels. Constrained and unconstrained air and constrained water were found to reduce the performance of the VN foam samples for all channel diameters tested in the study. Incorporating water into the channels at a channel diameter of 3/8 in. (0.95 cm) and leaving the channels open to a reservoir (unconstrained) was found to reduce peak headform acceleration on first impact by 11% (99 g) as compared to VN foam (110 g) without channels. This reduction is increased to 25% after six impacts (130 g versus 174 g, respectively), confirming the benefit of incorporating unconstrained fluid channels.

Fluid Viscosity Test

This test investigated the effects of viscous fluids in unconstrained 3/8 in. (0.95 cm) diameter channels. Solutions containing low concentrations of Glycerin, below 20% by weight, were found to reduce the performance of the sample. (This is presumably because the low Glycerin content breaks down the surface tension of water, reducing its resistance to flow, while not

sufficiently increasing the fluid viscosity). A range of Glycerin concentrations between 20% and 40% by weight were found to increase the energy absorbing capacity of the samples. The best combination was found using 3/8 in. (0.95 cm) diameter channels with an unconstrained 30% Glycerin solution. Although this produced the same range of peak headform acceleration on first impact when compared with water, it showed a marked improvement after six impacts. Average peak acceleration was 96 g for 30% Glycerin solution and 98 g for water for the first impacts. Peak acceleration reduced by 7% for 30% Glycerin after six impacts compared to water (121 g versus 130 g). When compared to EPS, the 30% Glycerin solution incorporated into VN foam was found to reduce peak headform acceleration by 16% (96 g vs 114 g) on first impact and by 50% on sixth impact (121 g vs 240 g). Samples testing Glycerin solutions higher than 40% Glycerin by weight were not found to provide any additional advantage.

Impact Force Comparison

Incorporating fluid channels was found to significantly reduce the peak forces imparted to the headform (Fig. 4). For EPS, the peak impact force after first impact was 6.5 kN, which was reduced to 6.16 kN by the use of VN foam. Use of unconstrained water in 3/8 in. diameter channels reduced the impact force of the first impact to 5.46 kN and this was further reduced to 5.0 kN by the use of 30% Glycerin solution in 3/8 in. channels. 30% Glycerin solution thus reduced the peak force by 23% over EPS. In both cases the impact energy was 86.2 J, however, the fluid channels presumably better distributed the energy away from the point of impact. The impact duration also increased by 27% by the use of 30% Glycerin solution compared to EPS after first impact. After the sixth impact, the peak force imparted to the head increased to 6.5 kN or by 30%, when compared to first impact performance for VN foam sample incorporating aqueous 30% Glycerin solution in 3/8 in. (0.95 cm) diameter. In comparison, for EPS samples,

the forces acting on the headform were nearly doubled over six impacts (13.4 kN), while for samples of VN foam without fluid channels the forces increased by 59% (9.77 kN). For the case of water, the increase is 32% to 7.21 kN. The duration of impact was also substantially increased by 57% for VN sample with 3/8 in. and 30% Glycerin, compared to EPS. Traces shown in Fig. 4 are each for a single impulse with peak force close to the mean peak force of six trials for each material.

Head Injury Criteria

As shown in Fig. 5 a significant reduction in the Head Injury Criterion (HIC) [12] is achieved by the use of VN foam when compared to EPS. This may be attributed to the better energy absorbing capacity of VN foam, deforming at a slower rate during impact. HIC values for EPS increased by 188% over six impacts, producing values in excess of the standard threshold value of 700 [13]. The HIC value for EPS after first impact was 252 which increased to 727 for the 6th impact. This confirmed that EPS was an unsuitable material for multiple impact applications. In contrast, samples incorporating unconstrained fluid channels into VN foam produced lower average HIC values than VN foam without any channels. Samples containing unconstrained 30% Glycerin solution produced a first impact HIC value of 138, which increased by only 27.5% to 177 after six impacts. Error bars in Fig. 5 indicate standard error for six samples.

Some weight penalty, of course, is associated with VN foam and incorporating fluid channels into it. VN foam itself was nearly twice the weight of an equal volume of EPS. With the addition of fluid channels the weight of the sample increased further, with a sample containing aqueous 30% weight Glycerin solution weighing over four times more than the same sample size of EPS. Further research in the use of thinner VN foam samples should be carried out.

One concern about the use of Glycerin in ski helmets is its change in viscosity and phase at lower temperatures. Viscosity of 30% Glycerin solution at 20°C is 2.5 mPa s [14]. At -5°C it increases to 6.5 mPa s, over a two-fold increase. The freezing point of 30% Glycerin mixture is -9.5°C. Usual temperatures at skiing locations are in the range of 0 to -10°C or even lower. The liner around Glycerin and the helmet shell will provide some level of thermal protection to prevent freezing. Nonetheless, more detailed analysis is required to find an optimum fluid for use at sub-zero temperatures. The scope of this experimental study was restricted only to standard room temperature of 20°C and was not intended to reproduce environmental factors, which should be considered in any practical implementation.

Conclusions

A significant reduction in peak headform acceleration can be achieved by incorporating fluid channels into VN foam. Initial experiments verified that a resilient Vinyl Nitrile foam like DERTEX VN600 outperformed EPS on first impact characteristics and on all repeated impacts on a flat, solid anvil. Repeated impact testing found a large reduction in the energy absorbing capacity of the EPS lining after multiple impacts, while VN foam responded significantly better. A system incorporating unconstrained fluid channels was developed and proved to increase the performance of the sample when compared with VN foam without any channels. Best results were achieved using an aqueous solution containing 30% Glycerin by weight (Viscosity: 2.13 mPa s), unconstrained, in five 3/8 in. (0.95 cm) diameter channels. These samples provided a 17% reduction in peak headform acceleration on first impact and a 50% reduction on sixth impact compared to an EPS foam sample. A patent application [15] based on our novel concept of fluid filled channels in helmet liner is under review.

Acknowledgements

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List of Figure Captions

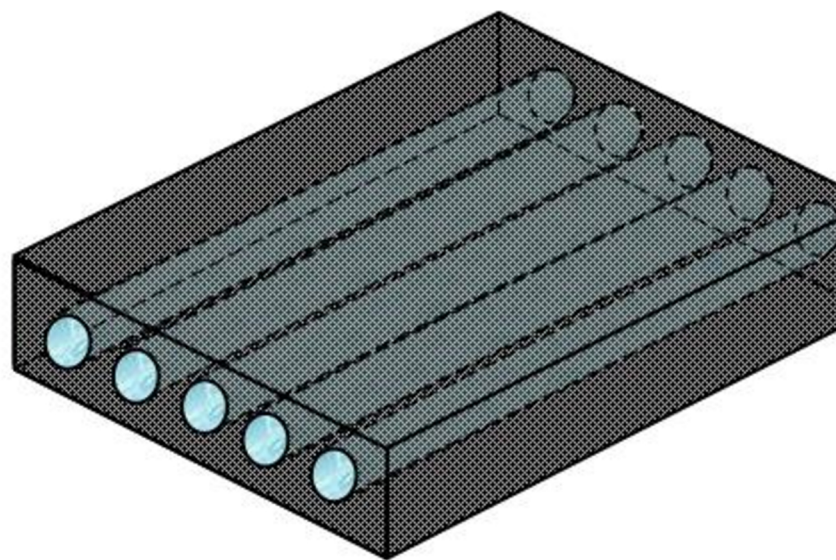
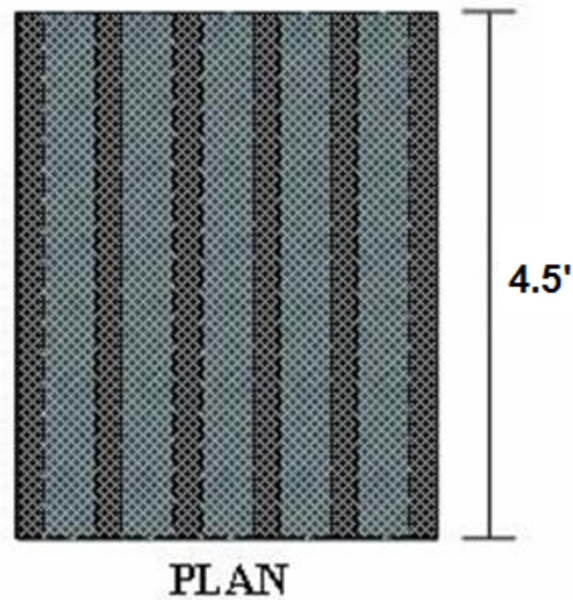
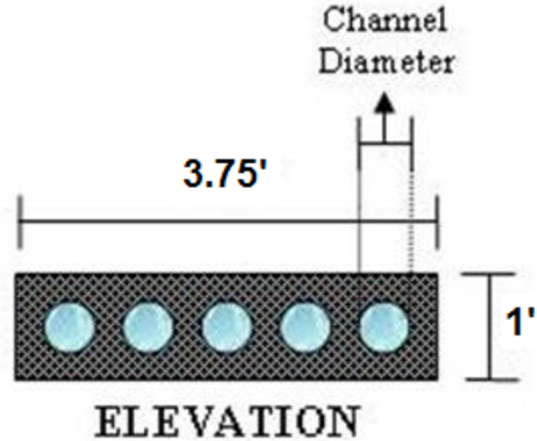
FIG 1-*Sample Dimensions (DERTEX VN600 sample with Fluid Channels).*

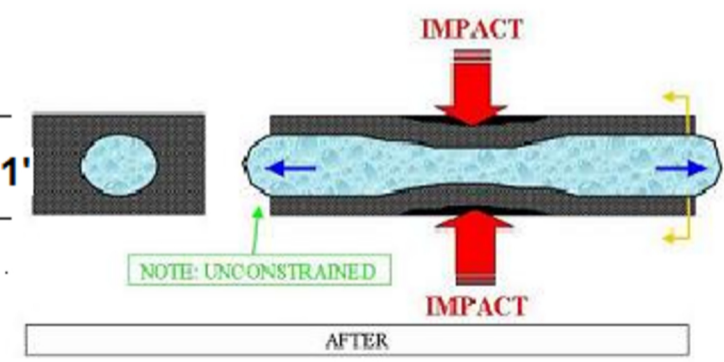
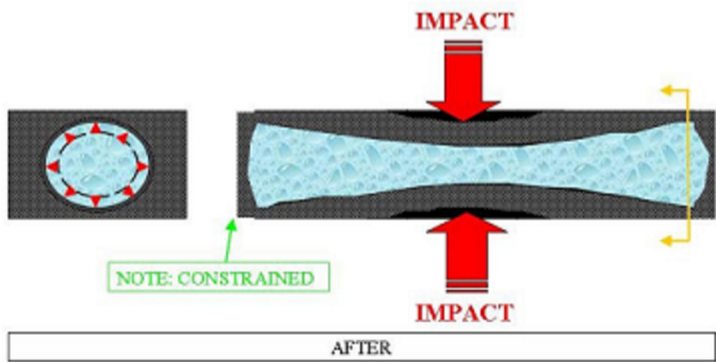
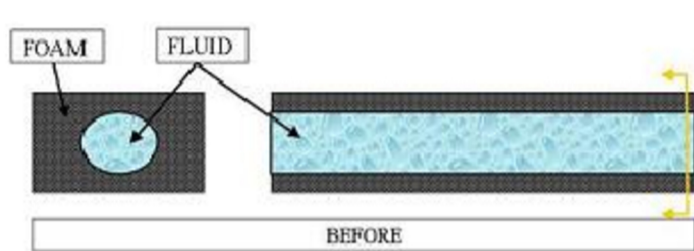
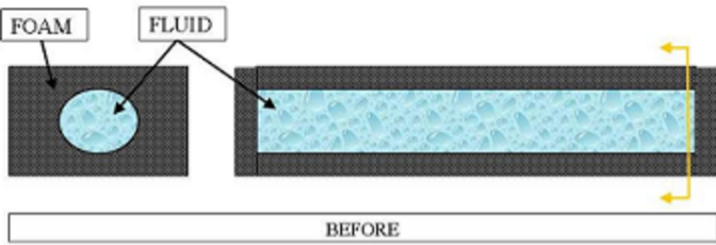
FIG 2-*Fluid constrained and un-constrained in channel (cross-section of one particular channel).*

FIG 3-*Effect of Repeated Impacts on Fluid Liner: Un-constrained fluids at 3/8 in. channel diameter (n=6, standard error shown).*

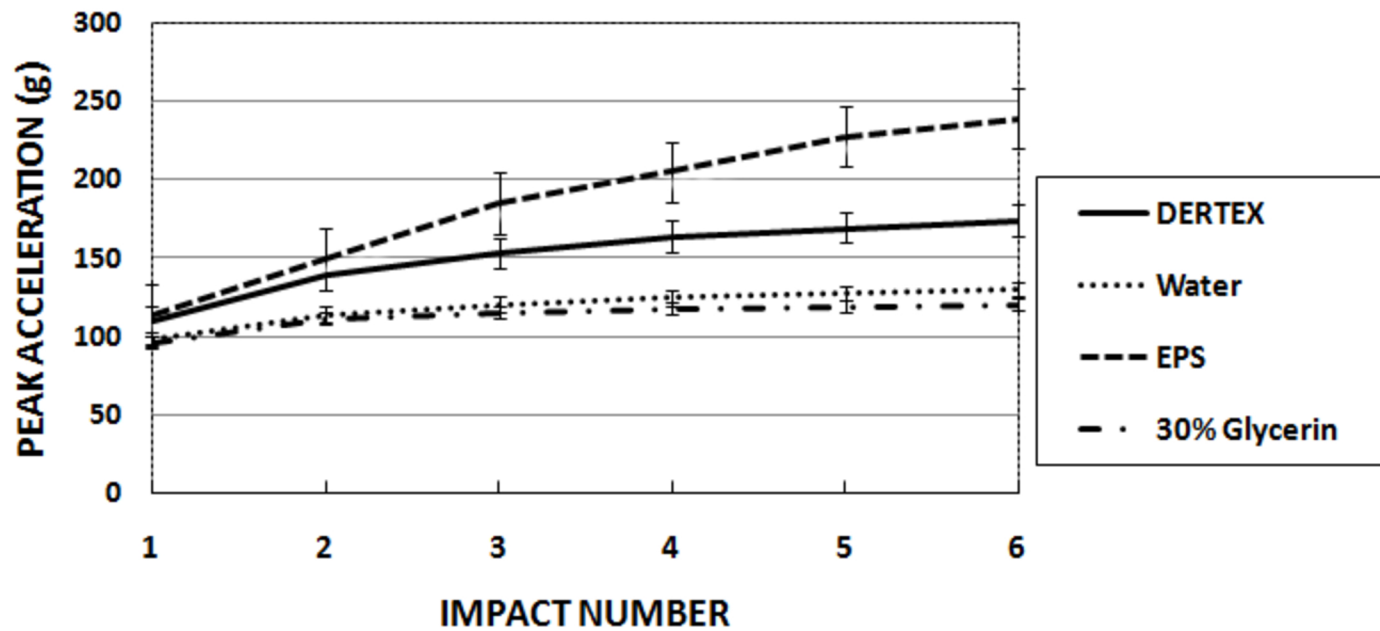
FIG 4-*Comparison of peak headform forces during 1st and 6th impact. Traces shown are each for a single impulse with peak force close to the mean peak force of six trials for each material.*

FIG 5-*HIC values for associated samples after multiple impacts (n=6, standard error shown).*

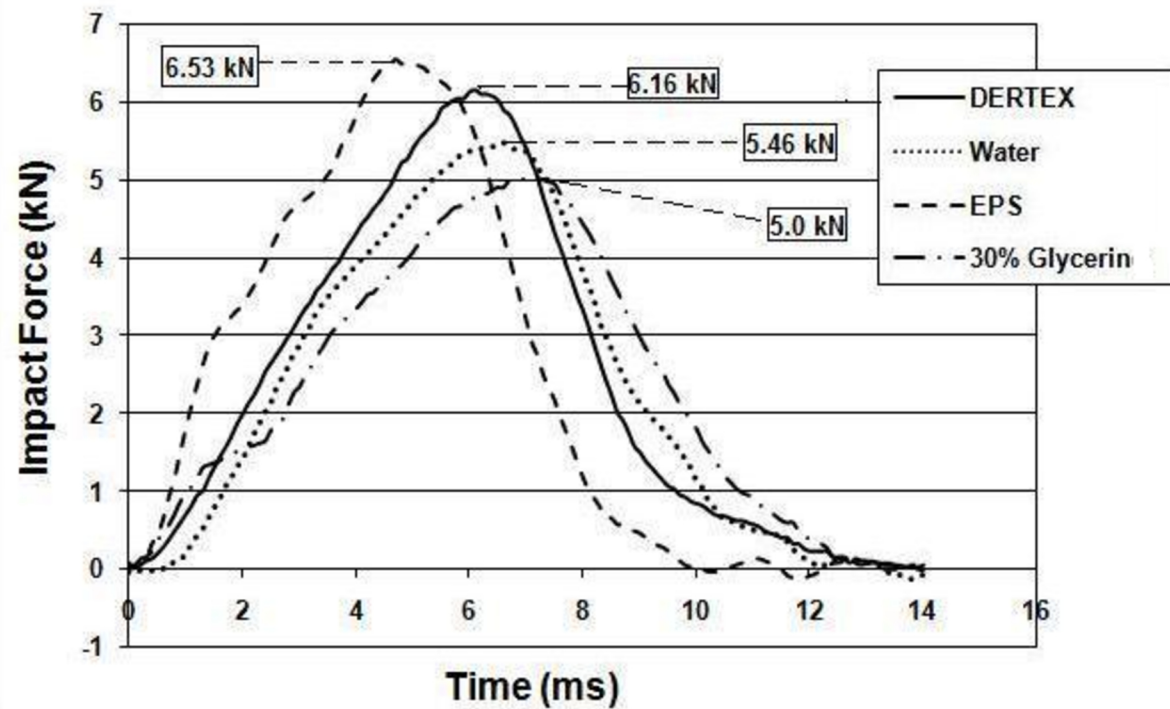




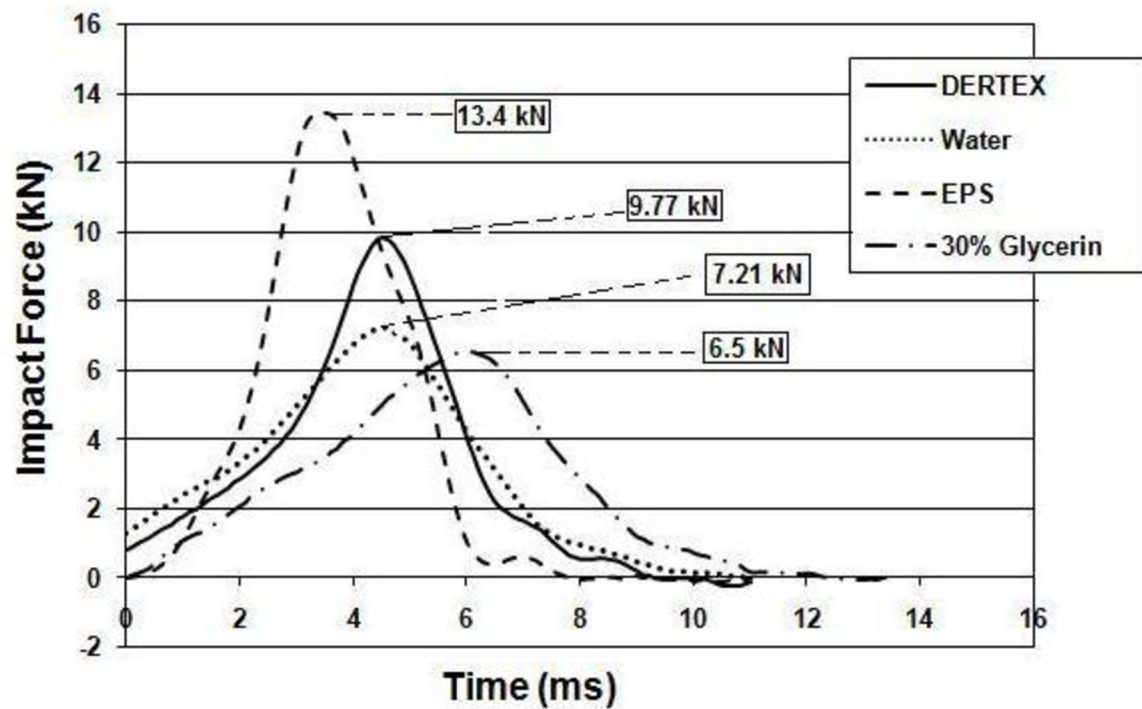
Peak Acceleration



Force on 1st Impact



Force on 6th Impact



Head Injury Criteria (HIC)

