Analysis of current Traumatic Brain Injuries, concussion rates, helmet protection standards, helmet design deficiencies, and suggestions for basic helmet improvement in youth ice hockey and other contact sports

David J Millar Jan 2011 DRAFT 8.1

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Abstract

Background Ice hockey is a contact sport with an implied risk of injury due to contact with the ice, boards, players, goals, and other equipment. Helmets and facial protection will not eliminate the possibility of all injuries but they have been shown to reduce some injuries.

Purpose To evaluate the current helmet standards used in ice hockey as compared to other contact sports. The current research in concussions (TBI). The current design, materials and processes used in the production of helmets. Recommend design and standards changes to reduce the probability of TBI, head, neck and facial injuries in youth ice hockey. These changes have applications in football and lacrosse as well.

Methods Current research materials were reviewed and helmets were purchased for testing, measurements, and evaluation of construction.

Results Design deficiencies and areas for improvement were noted in all contact sports helmets tested. The probability of TBI AIS4 can be reduced by > 6 percentage points.

Conclusion Changing the design, liner materials, construction, manufacturing, and assembly techniques that are currently available and used in helmet manufacturing today along with raising the helmet testing standards can reduce the probability of TBI and mTBI in contact sports.

Materials reviewed et al.

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Intentional verses unintentional contact as a mechanism of injury in youth ice hockey
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Blackman E G 2010

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Trumble C C, McEntire B J, Crowley J S

A prospective study of physician-observed concussions during junior ice hockey:

Implications for incident rates

Paul Sean Echlin, M.D., Charles H. Tator, M.D., Ph.D., Michael D. Cusimano, M.D., Ph.D., Robert C. Cantu, M.D., Jack E. Taunton, M.D., Ross E. G. Upshur, M.D., Craig R. Hall, Ph.D., Andrew M. Johnson, Ph.D., Lorie A. Forwell, M.Sc.P.T., and Elaine N. Skopelja, M.A.L.S. 2010

Analysis

Ice hockey is a growing sport in the United States with > 351,000 male and female youth participating[1]. One current study[2] showed (17of 67) 25% of 16 to 21 year old male youth players suffered 21 concussions, during 52 physician observed games. About 1 per 332 athlete game hours. These findings correspond to my observations of 23% (3 of 13) of 12 to 13 year old male youth players suffering concussions during 8 observed games in 2010. About 1 per 192 athlete game hours. Only lost time concussions were counted. Average return to play time was >5.5 days. Bell ringers, players shaking it off, or clearing the cobwebs and returning to play were observed but not counted. Other studies, et al. have shown concussion rates in youth ice hockey ranging from 6% to >30%, as high as 23 per 1000 player game hours in youth ice hockey compared to an estimated 29 per 1000 player game hours for the NHL[3 A]. These rates are much higher than the NCAA ISS reported 1.47 concussions per 1000 athlete game hours for mens ice hockey and 2.72 per 1000 athlete game hours for women's ice hockey. These rates are also much higher than the generally acceptable 5% concussion rate in football and the < 5% concussion rate in lacrosse. It would appear that concussions are under reported and there is no central tracking system in place for an accurate analysis of true concussion percentages.

The cost of sports related TBI (concussions) in the United States to the American health care system is approximately $56.3 billion dollars[4] per year, not to mention the quality of life issues the athletes have been known to suffer from TBI.

The ice hockey helmet standard ASTM F1045, currently the only standard accepted by HECC[5], NCAA, ACHA, and USA Hockey[6], are the lowest standards, lowest drop height (1m) lowest test energy level (51 joules) and the highest peak g's (300 pass/fail limit) of any contact sporting helmet allowed for use in the United States by any governing body. Currently football and lacrosse helmets are required by the NCAA and US Lacrosse to be certified by NOCSAE with an SI of < 1200, test energy levels of 115 joules and a pass/fail limit of 215[7] peak g's. The ice hockey testing standards have remained at this low level, below other contact sporting helmet test levels, against the advice[8] of the ATSM, that was presented to the HECC in 2000. ASTM F1045 test standard requires the helmet be dropped from a height of 1 meter (39 inches) with the helmet mounted to a 5 kilogram (11 pound) head form onto a MEP (modular elastomer programmer) rubber pad. The peak g's at any one location cannot exceed the 300 g pass/fail limit. Football and lacrosse helmets are tested by dropping them onto the same MEP from a height of 1.5 meters (60 inches) while mounted to a 5 kilogram (11 pound) head form and they cannot exceed the 1200 SI pass/fail limit NOCSAE standard. Compare the hockey helmet standard to the bicycle helmet standard and while the peak g's for the tests are the same, 300g pass/fail limit, the drop height for the bicycle helmet is 2 meters, twice that of hockey helmets. Ice hockey helmets should be tested at more realistic heights and by impacting them on a surface that more closely represents the hardness of ice. Ice has a Brinell hardness of about 4 at -5ºC[9]. This is almost the same Brinell hardness 4.2~4.3 as pure lead. The impact tests should also be changed to emulate realistic conditions encountered on the rink. A 1 meter (39”) test height more accurately represents the height of a 50th percentile 3.5 year old male. A 1.5 meter (60”) test height would more accurately represent a 50th percentile 13 year old male. The impact tests should also include anvils resembling the geometry of objects impacted during play. Impact data from ice hockey helmets equipped with sensors has shown that helmet impacts recorded during game play exceeded peak test impacts recorded in the laboratory[10].

Current studies on helmet impacts in football and hockey by Pellman, Ono, Post, Rousseau, et al, have shown that the threshold for the probability of mTBI to be much lower than any and all current helmet standards. The current data shows mTBI occurring >70% of the time with impacts ranging from 75g's~ 125g's and lasting from 14ms~16ms in duration in the NFL[11]. A concussion was recorded in youth ice hockey due to an 87g impact[12]. This falls within the range of recorded NFL data.

There is no current precise injury threshold for for mTBI, however peak linear acceleration have been reported to be somewhere in the range of 66g, 82g, and 106g for a 25%, 50%, 80% probability respectively of sustaining a concussion. Peak angular accelerations have been reported to be somewhere in the range of 4600 rad/s^2, 5900 rad/s^2, 7900 rad/sec^2 for a 25%, 50%, 80% probability of concussion[13].

Requiring all contact sports helmets to be tested to higher standards, higher energy levels, lower g's, less angular acceleration rad/sec^2, should reduce the probability of TBI.

Figure 1 is a commonly used concussion Traumatic Brain Injury (TBI) Abbreviated Injury Severity (AIS) chart. Figure 3 &4 are Head Injury Criteria (HIC) VS pad thickness.

Classification of TBI Severity (Hayes et al. 07)

Injury severity AIS	Severity code	Fatality rate (range %)
1	Minor	0.0
2	Moderate	0.1–0.4
3	Serious	0.8–2.1
4	Severe	7.9–10.6
5	Critical	53.1–58.4
6	Maximum (currently untreatable)	. . .

Figure 1 from Blackman E 2010

CSA as compared to HIC AIS4

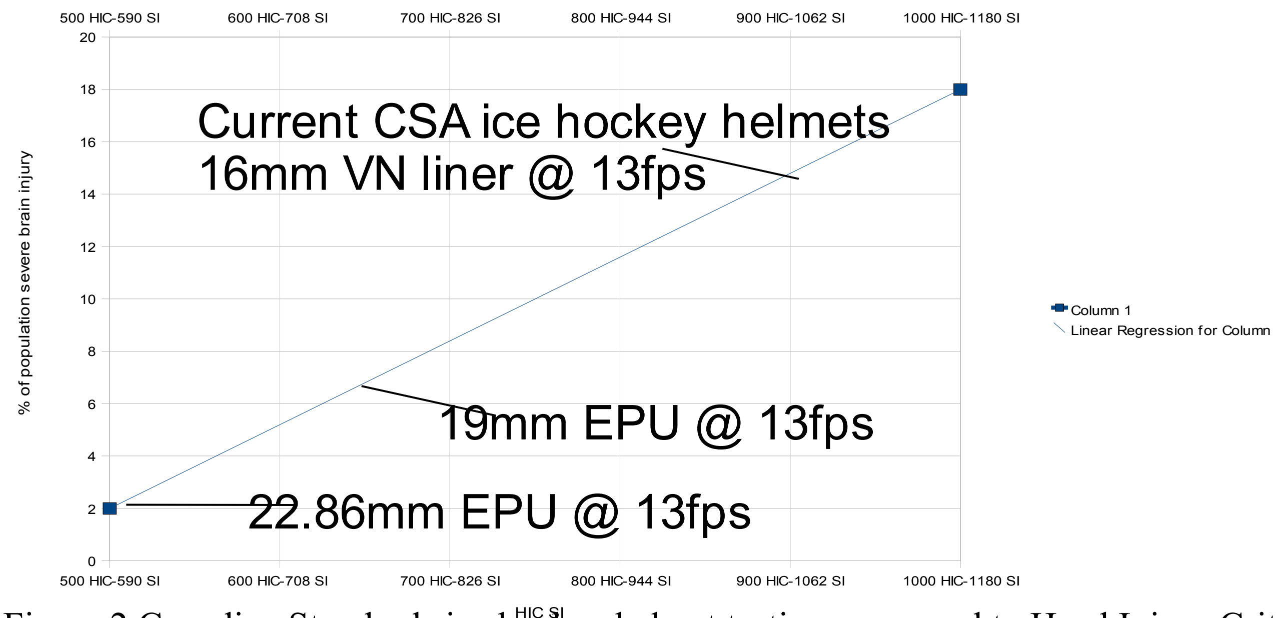


Figure 2 Canadian Standards ice hockey helmet testing compared to Head Injury Criteria pad thickness

HECC compared to HIC AIS4

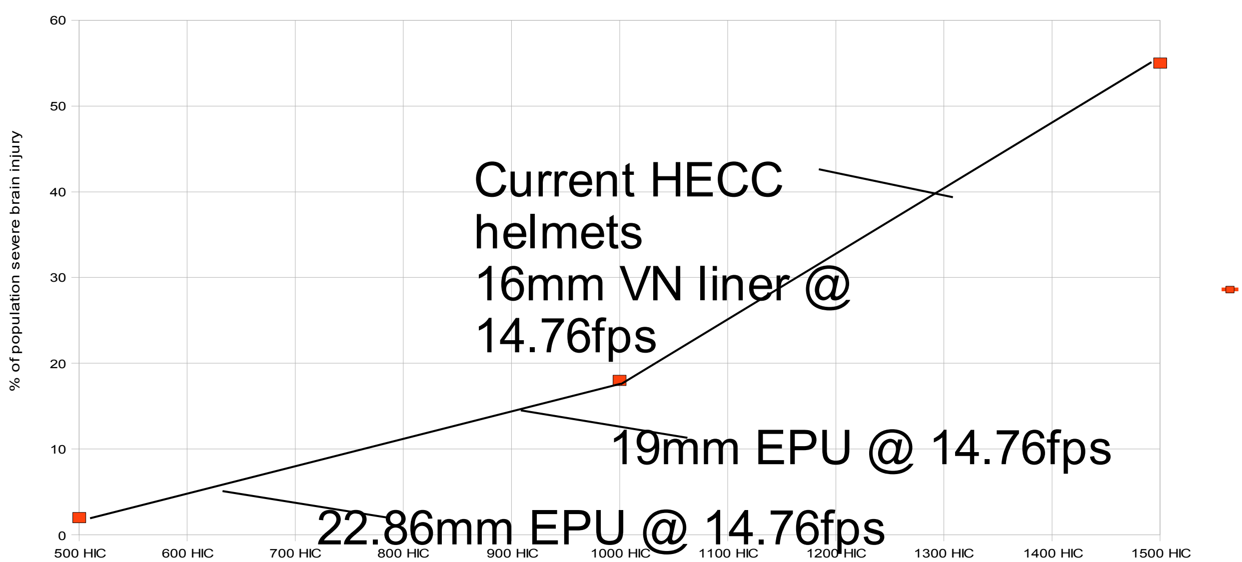
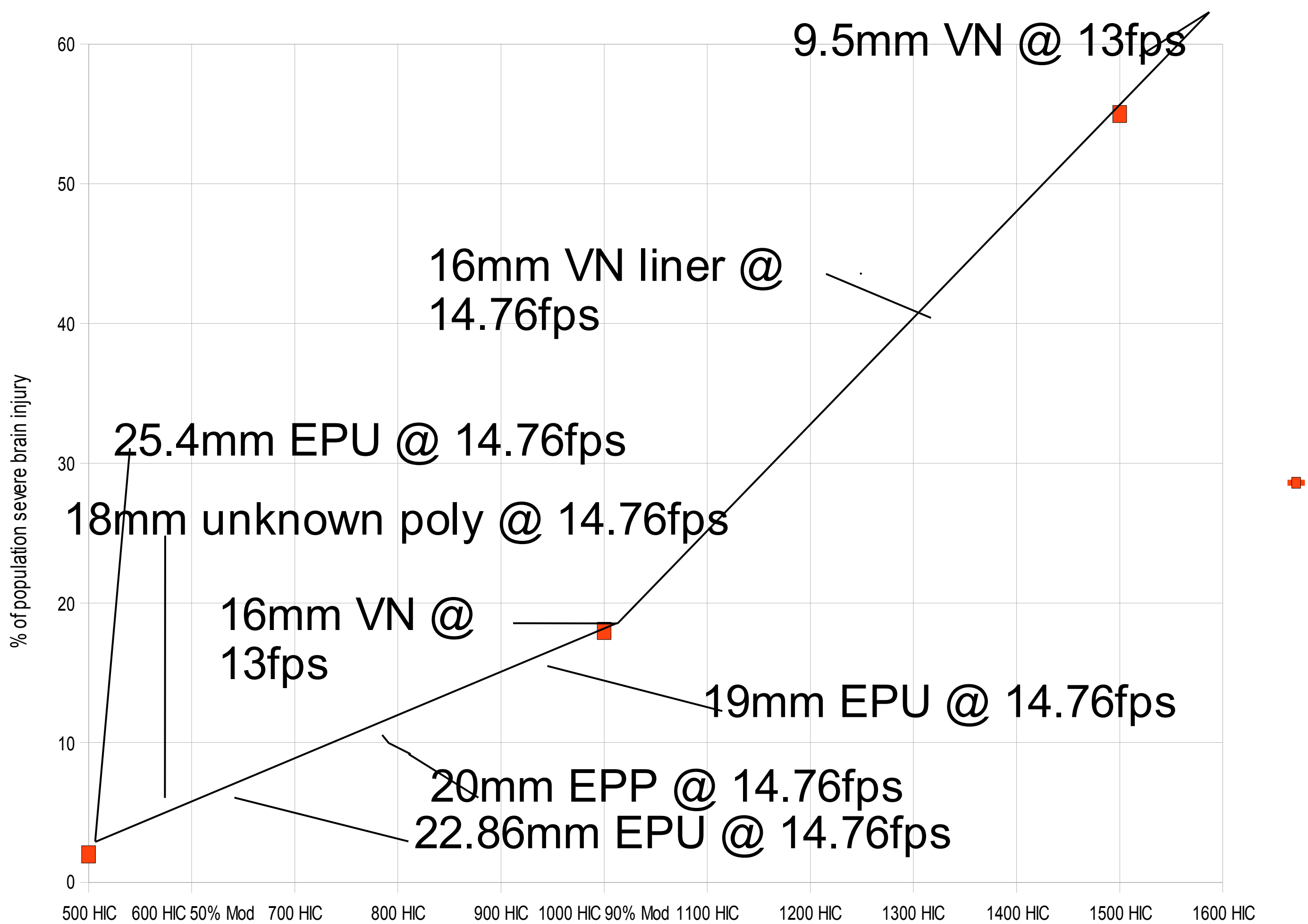


Figure 3 Hockey Equipment Certification Council Head Injury Criteria VS pad thickness

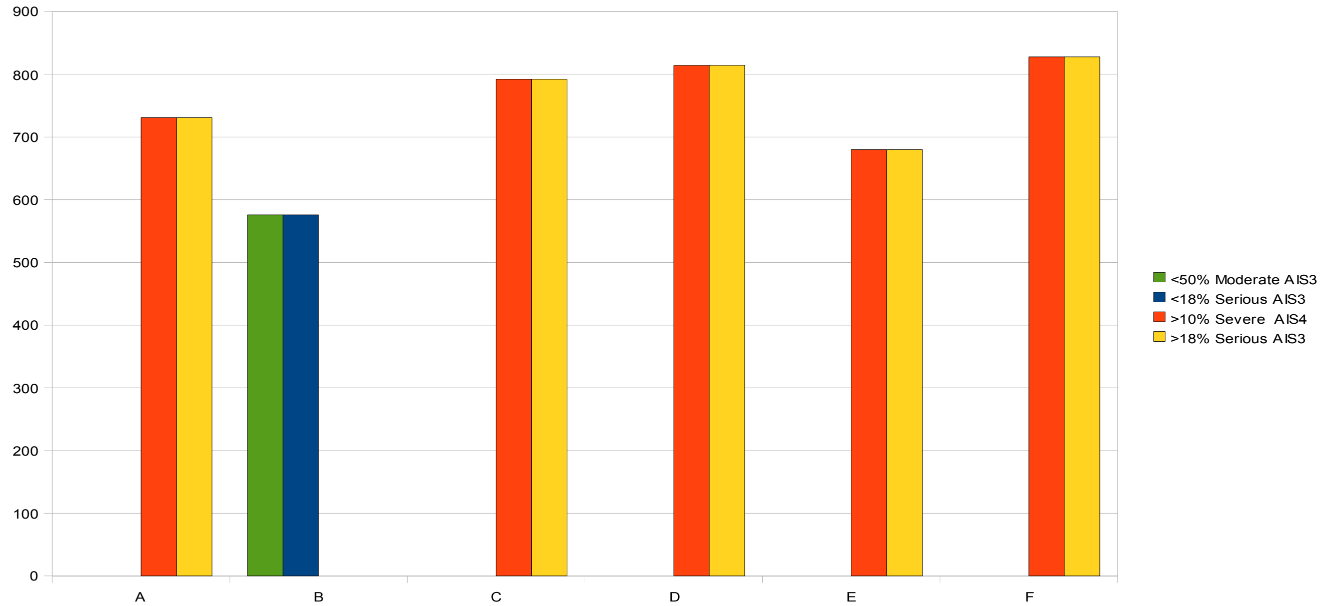
HIC AIS4 verses liner & thickness



Linear acceleration

Figure 6 Various foams and one unknown poly VS Head Injury Criteria
EPU was impact tested by LLNL as a flat pad not installed in a helmet. Helmet geometry may change the impact attenuation results of this pad.

6 current ice hockey helmets HIC AIS3/4



Mean HIC from impact site with the highest mean HIC, 6 sites, 3 impacts per site. Adapted from Giacomazzi 08

Figure 7 6 ice hockey helmets as compared to Head Injury Criterion and the probability of severity concussion.

Levels Of Consciousness In Relation To Head Injury Criteria (Payne, Patel 01)

Head Injury Criteria	AIS Code	Level Of Brain Concussion And Head Injury
135 – 519	1	Headache or dizziness
520 – 899	2	Unconscious less than 1 hour
900 – 1254	3	Unconscious 1 – 6 hours
1255 – 1574	4	Unconscious 6 – 24 hours
1575 – 1859	5	Unconscious greater than 25 hours – large hematoma
> 1860	6	Non survivable

Proposed HIC Tolerance Levels Correlated To Brain Injury (Payne, Patel 01)

Injury Level	Proposed Tolerance Level	Equivalent Acc g	Equivalent AIS	Equivalent Legislation	Equivalent Euro NCAP
	HIC (15 msec)	(For 3ms)		HIC	HIC
0 (No concussion)	< 150	<55	0	-	<650 Green
1 (No concussion)	< 150	<55	1	-	<650 Green
2 (Mild concussion <1hr)	150 – 500	55-90	2	BCT609 / ECE80 500	<650 Green
3 (Severe Concussion 1 – 24hr)	500 – 1800	90-150	3 / 4	FMVSS 208 1000 EC/79/96 1000	<650 Green 650 – 767 Yellow 767 – 883 Orange 883 – 1000 Brown >1000 Red
4 (Life threatening coma >24hr)	>1800	>150	5	-	-

Acceptable HIC levels according to the FMVSS 208 standard are 700. The IIHS report in 2009 rates HIC as follows: 560 Good, 700 marginal, and 840 poor.

Helmets

Various brands of helmets were purchased and tested. All of these helmets are currently available brand new for purchase at retail locations and are currently certified by the HECC, NOCSAE, or CPSC. Originally only ice hockey helmets were going to be included but a football, lacrosse and multi sport helmet were included in the research. Only the ice hockey helmets had test standard and expiration dates marked on the exterior of the shell in fine print. Current ice hockey helmets utilize three basic types of liners: Vinyl Nitrile, EPP, and a cylinder system. The limiting factor of any of these types of liner materials is the relatively small shell to head distance in certain areas of ice hockey helmets as compared to other sports helmets. One surprise finding was the large amount of void area between the shell and the liner material in various areas on all the contact sports helmets.

Helmet measurements	Shell thickness	Max outer shell to head form	Max void shell to liner	liner thickness min/max
Hockey helmet A	3mm	52mm	21mm	21mm/21mm
Hockey helmet B	3mm	50mm	12mm	10mm/18mm
Lacrosse helmet	3.5mm	47mm	7mm	11mm/22mm
Football helmet	4.5mm	50mm	16mm	22mm/28mm
Multi sport helmet*	3mm	44mm	<1mm	19mm/22mm

* Manufacturers thin fitting pads installed per the instructions

Figure 8 Measurements do not add up to total shell to head form due to voids between head form and liner.

Another concern is the head to liner voids from poor fitting helmets.
Angular acceleration has been the concern with increased shell diameter, however the unused volume, voids, between the liner and shell due to construction techniques suggests that more energy attenuating liner material could be fitted into current shell volumes without increasing shell size. This would provide a lower probability of linear concussions while not increasing the probability of a concussion from angular acceleration. The construction techniques in the Hockey helmet A, lacrosse helmet and football helmet all used flat foam liner material that was attached to the curved interior of the helmets shells. This created voids, Fig's 9 to 12, between the liner and the shell and also deformed the foam. In Fig 11 the unnecessary ridges on the helmet create extra weight, voids and increase the radius of the helmet. This in turn increases the risk of angular acceleration. In Fig's 13 to 16 the deformed foam had cells on the head side compressed and the shell side stretched reducing it's ability to attenuate linear impacts. Voids were also created due to the attachment points of the flat liners. It is suggested that all foam liners be molded to the interior contour of the helmet. This would allow more energy attenuation material and allow the foam to perform to it's intended design level. The multi sport helmet used a molded foam liner Fig 15 that resulted in < 1mm void between

the shell and liner. It has the highest test drop height, 2 meters, of any of the above helmets, and the same pass/fail 300g limit as the ice hockey helmets. It also has a smooth rounded shell design, the smallest head to exterior shell distance, 44mm, of any helmet tested and should have the lowest probability of concussion from angular acceleration due to the smaller radius.

Female athletes have a much higher concussion rate than male athletes[14] and youth athletes respond differently than adults to concussions[15]. This would indicate the need for different helmets and standards for youth males and all female athletes[16].

Figure 9 Lacrosse helmet flat liner pad to helmet shell 3.5mm gap.

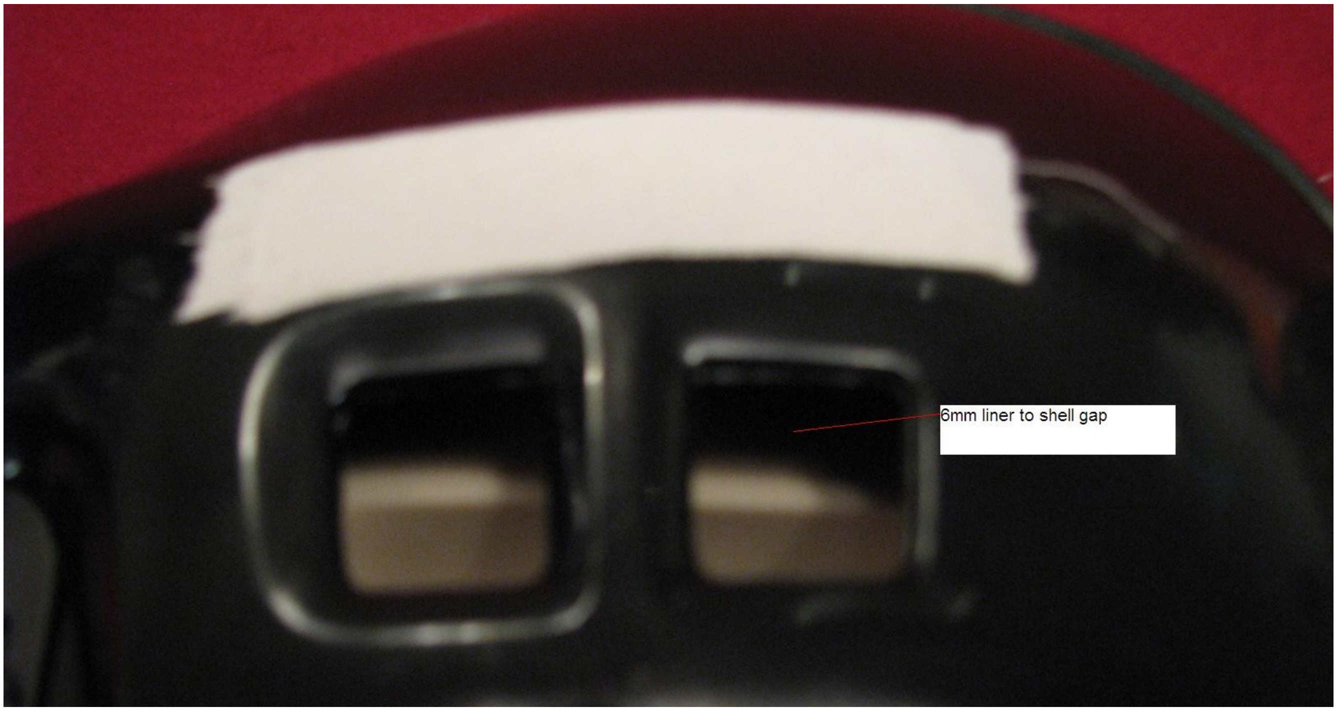


Figure 10 Ice hockey helmet flat liner to helmet shell 8mm gap.

Figure 11 Voids in ice hockey helmet.

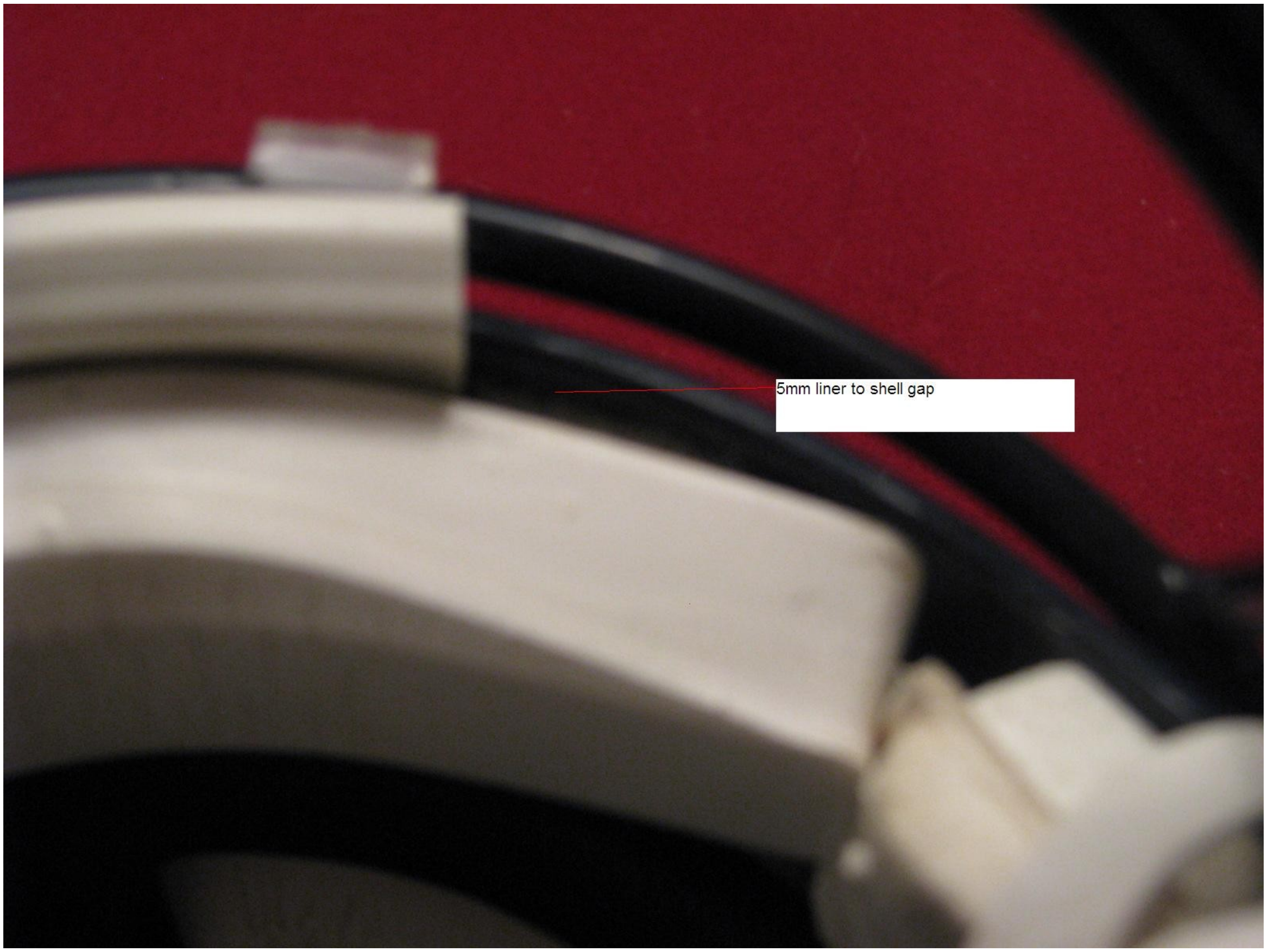


Figure 12 Football helmet flat liner to shell 5mm gap.

Figure 13 Lacrosse flat helmet liner deformation caused by fitting flat liner to curved surface of helmet. Foam cells in these areas are collapsed thereby limiting there ability to attenuate energy.

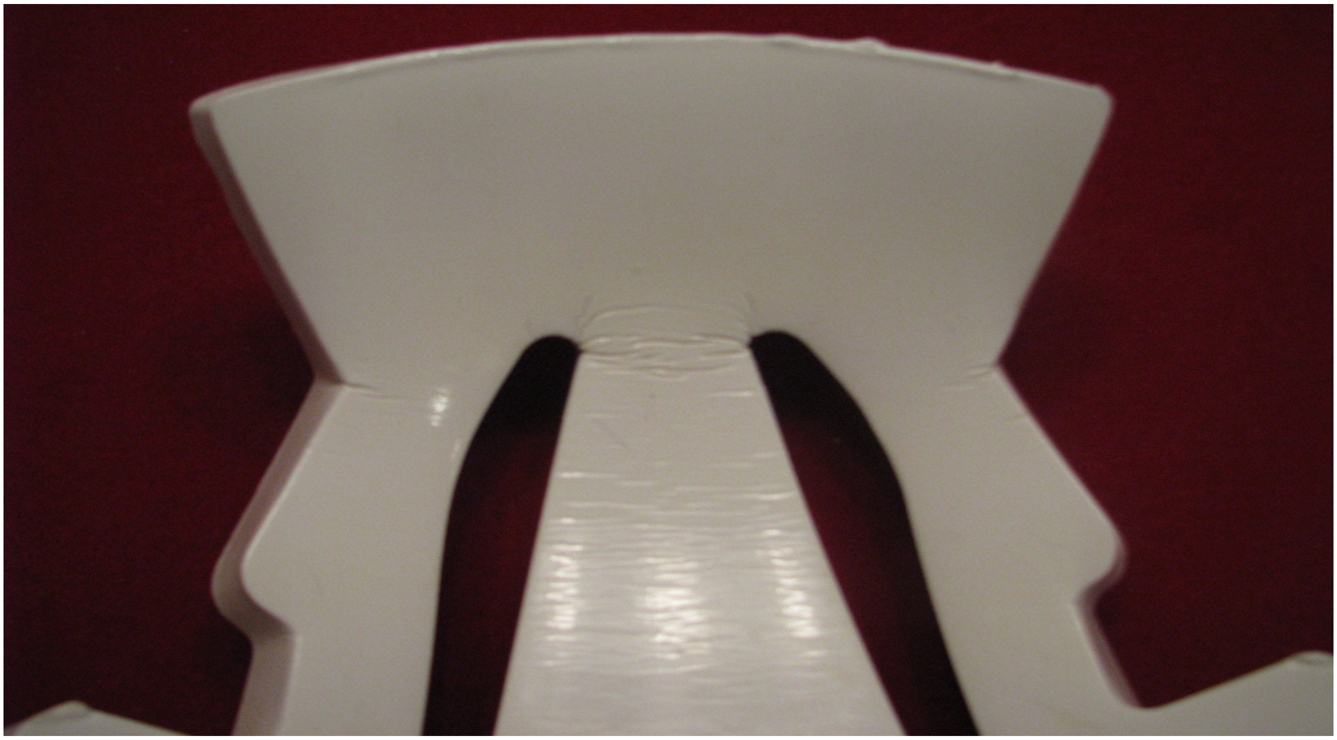


Fig 14 Flat pad removed from lacrosse helmet. Compression set of flat pad clearly visable.

Figure 15 Football flat helmet liner deformation caused by fitting flat liner to curved surface of helmet. Foam cells in these areas are collapsed thereby limiting there ability to attenuate energy.

Fig 16 Flat pad removed from football helmet. Compression set of pad clearly visable.

Figure 15 Multi sport helmet with a molded liner (removed) < 1mm liner to shell gap.

The new helmet liners could use a liner made up of multiple materials EPP is significantly better at reducing linear acceleration and Vinyl Nitrile is significantly better at reducing angular acceleration[10]. A total liner thickness of > 19mm of some combination of a EPP or other energy attenuating outer liner molded to the shell and an inner Vinyl Nitrile or other angular energy attenuating liner should reduce the probability of both linear and angular acceleration concussions without increasing current shell sizes or overall weight for helmets using foam liners. Fitted inner liners such as the TPL® (Thermo Plastic Liner) are similar to a boil and bite mouth piece. It is placed in an oven and heated, then placed on the head where it cools for a perfect fit. It is then attached to the helmets outer liner. Strain-rate dependent foams are also a possibility[17]. Further testing and research will be needed.
Protrusions from the helmets must also be reduced or eliminated to reduce the probability of angular accelerations. A smooth one piece shell will eliminate the probability and severity of some of the accelerations. The other issue is with facial protection attachment and construction increasing angular acceleration.

Facial protection

Facial protection design and mounting needs to be changed to minimize angular acceleration. Current facial protection in ice hockey football and lacrosse all have vertical bars mounted to the exterior of the horizontal bars and the face masks mounted to the exterior of the helmets. This arrangement increases the radius by > 3mm and creates the opportunity for increased angular acceleration. Flush mounting the face mask bars would reduce the radius by >3mm or allow an additional 1.5mm of energy attenuating liner material with a slightly larger shell while still decreasing the radius. Fig 16 & 17 These photos simulate the player in the silver mask hitting the player in the white mask. The vertical cage bars on the masks interlock, and the player in the white mask receives angular acceleration. This is true for all three sports as they all have vertical cage bars mounted to the exterior of the horizontal bars on the mask. The vertical bars on all three sports masks interlock in this manner. A helmet to helmet hit with the face masks interlocking will cause unwanted angular acceleration. It is recommended that vertical cage bars be made flush with horizontal cage bars. The masks should also be coated with a friction reducing material to help slide off objects and not induce angular acceleration. It is also recommended that cage bars be mounted flush with the helmet to eliminate the possibility of equipment causing unwanted angular acceleration. Figures 18 & 19 The flush mounting of the cage to helmet should be done by molding a ramp into the shell > 50% of the thickness of the cage. Thereby the shell to head distance is not reduced and the cages will not produce unwanted angular acceleration due to cage to cage or equipment to cage impacts.

Fig 16

Fig 17

Fig 18

Fig 19

Chin strap construction

Chin strap construction in ice hockey should be of the 4 point mounting system type used in football and lacrosse. A study conducted by the University of Minnesota[7] has shown, even though HECC certification requires the face mask not to contact the face, 26 facial injuries to players requiring sutures. These injuries occurred over 3 ice hockey seasons with the players properly wearing certified helmets and facial protection. These failures to protect were presented to the HECC in 2000 along with recommended design changes. Another failure was brought to the attention of the HECC in 2010 Fig's 20 & 21. It is recommended that all three sports, ice hockey, football and lacrosse require the use of an energy attenuating foam lined 4 point chin strap.

Helmet retention has always been a concern. The 4 chin strap should be secured directly to the helmet and closed by using a YKK type buckle. The current pull the dot type fasteners have been shown to slip at 150 lbf and fail at lower force than the YKK type buckles, 195 lbf verses 215 lbf[18].

This would be a 10% improvement in helmet fastener strength over the current systems.

Fig 20 Failed HECC certified cage

Fig 21 Failed HECC certified cage failure front view.

Results

The results revealed all three contact sporting helmets had areas for improvement in utilizing volume available for energy attenuating liner material. Helmets with flat pad liners that take a compression set are still being manufactured and sold. Currently available materials, manufacturing processes, and techniques using todays current helmet shell volumes can reduce the probability of TBI AIS4 by > 6 percentage points and reduce the energy transmitted to the brain if available interior volume in the helmet is utilized with better fitting liner materials (with as little as 2 or 3mm's of additional energy attenuating liner material in current shell volumes). This will not only reduce linear acceleration to the brain but can also reduce angular acceleration to the brain, if the proper inner liner is used in conjunction with a smooth hard shell, flush low friction face mask bars, flush mounting the face mask to the helmet, and requiring energy absorbing chin straps. It is possible to reduce the radius of the helmet by 4.8%, 6.5mm's, along with reducing the weight of the helmet, by removing the unnecessary ridges and flush mounting the vertical face mask bars. The preferred option would be to reduce the radius by 3.5mm's, 2.4%, and increase the liner thickness by 3mm, 10%. Further research and testing will be required to determine the exact combination of, density, thickness, and materials used in the liners, to achieve these results. However both the HECC and NOCSAE specifically exclude equipment research from their research grant programs. Testing should also be done simulating helmet to helmet and body to helmet contacts using biofidelic head and neck forms.

Conclusion

All three contact sporting helmets had areas for improvement in utilizing volume available for energy attenuating liner material. These changes will not happen if the governing bodies and certifying organizations do not insist on tougher helmet testing requirements. Lower the maximum g's, ms duration, test for angular acceleration, and increase the energy level the helmets are tested at. HIC or SI should also be included in the certification process. Youth and females have different needs when it comes to TBI prevention. Simply strapping on a helmet designed for an adult male does not work for females and youth. NCAA women's ice hockey, no body checking allowed, has almost twice the incidence of concussion compared to NCAA mens, checking allowed, ice hockey. The first step in ice hockey would be to have USA hockey require and the HECC adopt new standards for testing all ice hockey helmets and possibly a different standard each for adult male, female, and youth helmets. Raising the test impact velocity to a minimum of 15.75fps, testing the helmets on flat, hemispheric, roll bar, and curbstone steel anvils to simulate impacts experienced on the ice, include an angular acceleration standard of < 5900 rad/sec^2 @ 16.4fps, and a HIC standard of < 600 or SI of < 720, will reduce the probability of TBI. The standard to which the helmet was certified, with a re certify by date, should be clearly marked on the exterior of all contact sporting helmets. This will remove old and helmets certified to a previous standard from play. Consumers should also have the option to make an informed buying decision when purchasing a helmet. Do they want to purchase a helmet that has a 2% probability of severe concussion HIC AIS4 or a helmet that has a 12% probability of severe concussion HIC AIS4? Most parents would want to stack the odds in their child's favor. These changes could potentially save the American medical system in excess of $200 million dollars every year.

The governing bodies and certifying organizations will not require these changes unless pressure is placed upon them.

1 USA Hockey NCAA, ACHA, IIHF et al. > = Certain youth house teams do not require membership in USA hockey,
2 Neurosurgical Focus 1 Nov 10 A prospective study of physician observed concussions during junior ice hockey.
3 ASTM meeting 2008 Smith A Stuart M Dodick D et al.
A The NHL does not require certified helmets. NHL players have also been known to modify (lighten/thin) helmets for less weight & better fit. Thin liners were tested in Safety in ice hockey 3rd volume 2000
4 Characteristics of head impacts sustained by youth ice hockey players 2008
5 Hockey Equipment Certification Counsel HECC web site www.hecc.org
6 USA Hockey web site www.usahockey.org
7 Football NOCSAE Doc ND002-98m09 and Lacrosse NOCSAE Doc ND041-05m08
8 Safety in ice hockey the third volume 2000
9 The American mineralogist Vol 43 Jan Feb 1958
10 Journal of ASTM International, Vol. 6, No. 6 Paper ID JAI101848
11 Helmet protection against traumatic brain injury Blackman E G
12 Characteristics of head impacts sustained by youth ice hockey players 2008
13 The effects of impact management materials in ice hockey helmets on head injury criteria Rousseau, Post et al 2009
14 Clinical ReportSport-Related Concussion in Children and Adolescents Mark E. Halstead, Kevin D. Walter 2010
15 PEDIATRICS Vol. 117 No. 4 April 2006, pp. 1359-1371 (doi:10.1542/peds.2005-0994)
16 Sports concussions & The immature brain Young athletes may be more vulnerable to mild brain injury Brenda Patoine 2011
10 The effects of impact management materials in ice hockey helmets on head injury criteria Rousseau, Post et al 2009
17 Proceedings of the IMPLAST 2010 Conference October 12-14 2010 Providence, Rhode Island USA © 2010 Society for Experimental Mechanics, Inc
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18 USAARL Report 2005-05