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Fit of bicycle safety helmets and risk of head injuries in children

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Abstract

***Background*—Although bicycle helmets are effective in preventing head and brain injury, some helmeted individuals nevertheless sustain head injury. One of the possible reasons may be poor fit of the helmet on the head. This study was undertaken to examine the relationship between helmet fit and risk of injury.**

***Methods*—1718 individuals who were helmeted riders in a crash were queried on helmet fit and position. A sample of 28 children 2–14 years of age who sustained a head injury while wearing a bicycle helmet and 98 helmeted individuals of the same age treated in the same hospital emergency departments for injuries other than to the head, underwent anthropometric measurements of helmet fit. Measurements were made of the child's head, the helmet, and on a cast made of the child's head.**

***Results*—Individuals whose helmets were reported to fit poorly had a 1.96-fold increased risk of head injury compared with those whose helmets fit well. Children with head injuries had helmets which were significantly wider than their heads compared with children without head injuries. Helmet fit was poorer among males and among younger children.**

***Conclusions*—Poor fit of helmets may be associated with an increased risk of head injury in children, especially in males. Helmets may not be designed to provide optimal protection.**

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Over the last decade, a sizable body of information has been assembled supporting the effectiveness of helmets in decreasing the risk of bicycle related head trauma.[1–6] Helmets appear to be very effective; best current estimates are that helmets decrease the risk of head injury by 85% and brain injury by 88%.[1]

All studies on helmet effectiveness, however, do report some individuals who sustain head or brain injury despite use of a helmet.[1–6] There are a number of reasons why helmeted cyclists might be injured, including: (1) the crash forces might exceed the design tolerance of the helmet; this may be particularly the case for injuries involving collisions with motor vehicles; (2) the impact may occur outside of the design line of the helmet, injuring the cranium below the helmet line; (3) the retention system may fail, allowing the helmet to shift substantially or even to come off during the crash; (4) the helmet may be worn improperly, on the back of the head "bonnet style"; and (5) the helmet may not fit properly, thereby subverting their protective effects.

The present study was conducted to examine the empirical data on helmet fit and risk of head injury among cyclists and test the hypotheses above.

Methods

This study was part of a larger case-control study on the effectiveness of bicycle helmets in preventing bicycle related head and brain injury.[2] The 3385 individuals for the larger study were recruited from patients attending one of seven Puget Sound hospital emergency departments for the care of a bicycle related injury. Patients, and parents for those under age 18, were sent a questionnaire within seven to 14 days of the crash inquiring about the circumstances of the crash and helmet use. Data on injuries were abstracted from the emergency department record. Questionnaire information was validated against the medical record.

In the present study, only helmeted subjects were included. The 1718 helmeted subjects from the larger study were asked to report on the fit of their helmet and on the position of the helmet on their head at the time of the crash. To examine the relationship between helmet fit and head shape, we obtained a convenience sample of 28 children 2–14 years of age who sustained a head injury despite helmet use and 98 children who hit their head, helmet, or face but did not have any head injury. These children were selected on the basis of location close to the study site and willingness to participate in the study. Head injury was defined as in our prior reports[1 2]: injury to the scalp, including the forehead, skull, or brain. This latter group of 126 children were paid 20 dollars to compensate them for the time spent participating in the study. Subjects were also reimbursed for the cost of the helmet, which was kept for further examination as described below. Informed consent was obtained from participants and their parents. The study was approved by the Institutional Review Boards of the University of Washington, Children's Hospital and Regional Medical Center and participating hospitals.

MEASUREMENT OF HEAD SIZE AND SHAPE

Head shape and helmet fit were examined for these 126 children using techniques developed for the manufacture of helmets used to treat

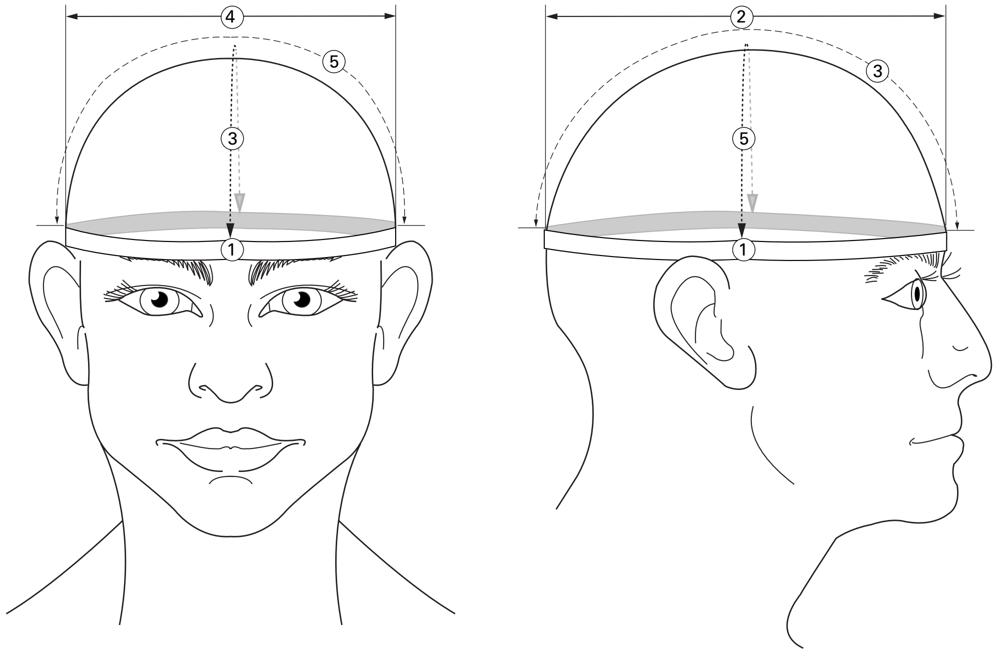

Figure 1 Measurements made on the child's head. 1 = occipital frontal circumference, 2 = anterior-posterior length, 3 = anterior-posterior arc, 4 = head width, and 5 = lateral arc.

positional cranial deformities.[7] Examiners were unaware of the type of injury the child had sustained. The examiner asked each child to put their helmet on and fasten it "as they usually wear it". The following direct measurements were made on the child's head using standard anthropometric techniques, as shown in fig 1. *Occipital frontal circumference* was the largest circumference of the head measured with a flexible tape measure. The measuring tape was then left in position. The *anterior-posterior length* was the maximum dimension of the sagittal axis of the skull. The *anterior-posterior arc* is the distance over the vault from the frontal to the occipital points on the cephalic edge of the measuring tape. The *head width* is the maximum biparietal diameter recorded between the most lateral points of the parietal bones. The *lateral arc* is the maximum distance across the vault between the most lateral points of the parietal bones to the cephalic edge of the measuring tape.

Casts of children's heads were made using techniques previously described for the construction of helmets for children with cranial deformities.[7] Briefly, a thin stocking cap was placed over the child's head after all hair ornaments were removed. The child was then asked to put on the helmet in the position it is normally worn, and a marking pen was used to trace the outline of the lower rim of the polystyrene liner on the stocking cap. This allowed us to record the orientation of the helmet to the head cast. The helmet was then removed and the external auditory canals and outline of both ears were marked for reference on the stocking cap. The stocking cap was then covered with plaster, allowed to harden for approximately three minutes, and then removed.

When fully dry, a number of measurements were then taken directly from the plaster cast

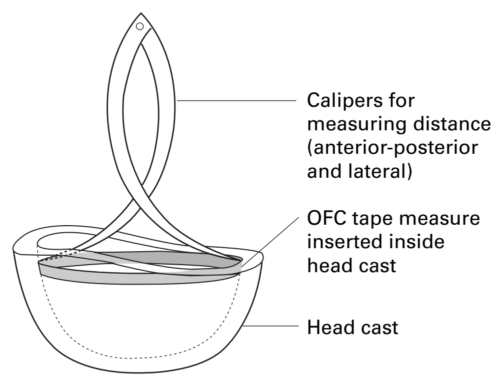

Figure 2 Measurements made on the head cast (OFC = occipital frontal circumference).

(fig 2). A flexible measuring tape was pre-set at the length of the occipital frontal circumference previously measured directly from the child's head, and placed inside the cast. It was oriented to match the anterior-posterior arc and lateral arc lengths recorded from direct measurement of the child's head. The cephalic edge of the tape was then marked on the cast in anterior, posterior, and lateral positions. The occipital frontal circumference, anterior-posterior arc, lateral arc, anterior-posterior, and lateral distances were then measured from the inner surface of the cast. The volume of the head (cephalic to the occipital frontal circumference) was measured by inserting a thin plastic bag, filling the mold with water to the level of the previously marked occipital frontal circumference location, and then measuring this volume of water. The depth was measured as the distance between the occipital frontal circumference water level and the most cephalic point on the cast.

MEASUREMENTS MADE FROM THE HELMET

All pads were removed from the helmet. Measurements were taken to reflect the homologous

Table 1 Self reported helmet fit and risk of head injury in bicycle crashes (percentages)

	All (n=1718)	Head injured (n=222)	Non-head injured (n=1496)	Odds ratio* (95% CI)
Fit				
Excellent	65	59	66	1.00
Good	28	31	27	1.26 (0.91 to 1.75)
Fair	2	3	2	1.68 (0.61 to 3.98)
Poor	4	7	4	1.96 (1.10 to 3.75)
Position				
Center	84	79	85	1.00
Posterior	13	18	13	1.52 (1.02 to 2.26)
Side	1	2	1	1.13 (0.26 to 3.72)
Helmet came off during crash	4	9	3	3.25 (1.82 to 5.75)

*Adjusting for crash severity did not produce a significant change in the odds ratio; therefore, crude odds ratios are presented. CI = confidence interval.

Table 2 Comparison of helmet minus head cast measurements in head injured and non-head injured children

Characteristic*	Cases (n=22)	Controls (n=73)	Two tailed p value†
Helmet minus head cast measurement (mean (SD) in cm and ml)			
Circumference at rim	4.3 (2.5)	4.9 (2.4)	0.30
Anterior-posterior length	1.0 (1.5)	1.0 (2.2)	0.94
Width	**1.7 (0.9)**	**1.1 (1.9)**	**0.05**
Length of anterior-posterior arc	2.7 (2.0)	3.1 (2.2)	0.43
Length of width arc	2.4 (2.0)	2.2 (2.7)	0.83
Depth (helmet rim to top)	1.0 (1.1)	0.7 (1.0)	0.19
Volume (helmet rim to top)	518 (227)	458 (282)	0.36

*See accompanying protocol for measurement definitions based on the actual orientation of the helmet on the head.
† *t* test for means.

Table 3 Variation of differences between helmet and head measurements by age group

Characteristic*	Young (2–6 years) (n=38)	Medium (7–9 years) (n=44)	Old (10–14 years) (n=44)	Two tailed p value
Helmet minus head cast measurement (mean (SD) in cm and ml)				
Circumference at rim	4.2 (2.4)	5.3 (2.0)	4.9 (2.8)	0.22
Anterior-posterior length	0.7 (2.5)	1.2 (1.2)	1.0 (2.2)	0.64
Width	1.6 (0.9)	1.6 (0.7)	0.7 (2.6)	0.049
Length of anterior-posterior arc	3.6 (1.9)	2.6 (1.7)	3.1 (2.7)	0.23
Length of width arc	2.3 (2.1)	2.5 (2.4)	2.0 (3.0)	0.71
Depth (helmet rim to top)	1.2 (1.1)	0.5 (1.0)	0.5 (0.9)	0.007
Volume (helmet rim to top)	551 (276)	438 (303)	436 (226)	0.16

*See accompanying protocol for measurement definitions based on the actual orientation of the helmet on the head.

positions on the head cast and helmet relative to the way the helmet was *actually* worn. The orientation of the helmet on the head was marked by the outline of the helmet's lower rim on the head stocking. The anterior-posterior arc, lateral arc, anterior-posterior distance, lateral distance, and the circumference at the level of the outlined helmet rim were then recorded from the head mold. The helmet was filled with water to a depth to match the water depth inside the head cast, and the position of the water level was marked in the anterior, posterior, and lateral positions. This level should be homologous to the position of the head occipital frontal circumference line. The water volume and depth at the helmet rim outline were recorded. The orientation of the helmet to the head was recorded by measuring the distance from the front rim outline on the stocking cap to the front occipital frontal circumference line previously marked. Helmet tilt was the distance between the helmet rim and the occipital frontal circumference mark and was recorded as a positive number if the helmet was tilted anteriorly and as a negative number if tilted posteriorly.

DATA ANALYSIS

The differences between the helmet and head casts were calculated for all measurements. Cases and controls were compared using *t* tests for continuous measures and χ^2 for categorical measures. Comparisons across age groups were done using one way analysis of variance.

Results

QUESTIONNAIRE DATA

Among all helmeted riders, 65% reported that the fit of their helmet was excellent at the time of the crash and an additional 28% reported the fit as good (table 1). However, 6% of subjects reported that the fit was fair or poor. At the time of the crash, 13% of subjects reported that the helmet tilted posteriorly, and 4% reported that the helmet came off. Subjects whose helmets fitted poorly had double the risk of head injury compared with those who reported the fit as excellent. Those who had helmets tipped posteriorly had a 52% greater risk of head injuries than those who wore their helmets centered on their heads. If the helmet came off during the crash, the risk of head injury more than tripled.

HEAD AND HELMET MEASUREMENT DATA

Overall, there were no significant differences in head size or shape among children sustaining head injury and those with injuries not involving the head. There were also no differences between the two groups on the amount of helmet tilt as they were actually worn. However, the head injured children had helmets that were significantly wider than their heads compared with children without head injuries (difference between helmet and head width 1.7 cm *v* 1.1 cm, p=0.05; table 2). This difference among head injured compared with non-head injured children was greater for males (2.1 cm *v* 1.3 cm, p=0.005) than for females (1.4 cm *v* 0.3 cm, p=0.98).

Significantly more of the head injured children (47.4%) had helmets 2 cm or more larger than the width of the head compared with controls (19.5%; odds ratio (OR) 3.72, 95% confidence interval (CI) 1.11 to 12.17). When examined by gender, this difference was found for males (OR 15.64, 95% CI 2.49 to 161.96) but not for females (OR 1.13, 95% CI 0.13 to 8.30).

As shown in table 3, there were significant differences between the different age groups on the differences between the helmet and head measurements. The differences in width and depth were significantly greater in younger children than older children, that is helmets appear to fit better in older children. Fifty eight per cent of children under the age of 10 had differences in width of 1.25 cm or greater compared with only 37% of those 10 and older (OR 2.37, 95% CI .93 to 6.12).

Discussion

Prior studies by our group and others indicate that helmets substantially decrease the risk of head and brain injuries.[1–6] The current study indicates that poor fit of helmets substantially lessens their protective effect. Riders whose helmets fit poorly have double the risk of head injury than helmeted riders whose helmets fit well.

This study suggests that the width of helmets in children compared with their heads may be the most important factor in contributing to the poor fit, which, in turn, results in lowered protective effect of helmets. Poor fit appeared to be a greater problem among younger children and among males in this sample.

This finding agrees with that of Bradtmiller and Kristensen who used a low level laser scanner to examine the size and shape of children's heads.[8] They concluded that helmets needed to come in a variety of widths (at least two) in order to accommodate children's head shape and thus achieve satisfactory helmet fit.

These mismatches in fit could increase the risk of injury in a number of ways. First, the increased distance between the head and the helmet may allow the head, and hence the brain, to accelerate during a crash before it comes into contact with the energy absorbing liner. This acceleration may thus undermine the ability of the liner to absorb the forces of the impact, resulting in brain injury. This increased space between the head and helmet cannot be adequately compensated for by soft fitting pads. These pads allow the head and brain to accelerate as well and are not designed for energy absorption. Second, while the study did not provide any direct association between helmet fit and helmets moving out of proper position, helmets that are too large in any dimension may be more likely to move out of correct position while being worn or during a crash, leaving portions of the head and brain unprotected. Poor fit cannot be adequately compensated by the helmet retention system because of the limitations of tightening straps on a child's jaw and the more oblique angles of a child's jaw in relation to the skull.

This study also developed a simple method to measure the fit of helmets. Children were used as subjects because our anecdotal experience was that many children wear their helmets out of position, and this might be related to poor fit. In addition, many parents reported that they had difficulty fitting helmets to their children's heads. Standards organizations and manufacturers have also been concerned about the number of sizes of helmets which should be offered to insure proper fit.

Using techniques adapted from craniofacial dysmorphology studies, we developed a protocol for measuring children's heads and helmets, and examined differences between the two. The head casts were made simply to provide a permanent record of the child's head that could be measured repeatedly and in a variety of ways. Since the one difference between cases and controls was width, a simple caliper like device to measure head width and compare it with helmet standards may be the only equipment needed to fit helmets properly.

There are a number of limitations to this study. First, the measurement study was limited only to children. Results may not be applicable to adults. With limited resources, and based on our own empirical experiences in estimating the fit of helmets to children's head, we believed that the yield of the study would be highest among children because fit seemed poorest in this age group.

Second, the measurement sample was a convenience sample and was small, limiting conclusions about differences that were not statistically significant. This was in part due to the fact that helmets are highly protective, and the number of helmeted children with head injury was limited. Biases from the convenience sample technique may have been introduced and are not quantifiable.

Finally, the techniques used in this study have not been previously applied to the examination of bicycle helmets. Nevertheless, the measurements were conducted by a team skilled in craniofacial dysmorphology, and most of the measurements are standard in the anthropometric literature. No allowance was made for the loss in volume of water due to bulging of the thin plastic bag into vent holes. This loss however would be expected to be small.

Implications for prevention

Poor fit of helmets may be associated with an increased risk of head and brain injury. It is clear from this work that helmets do not fit some children well. Helmets may need to be redesigned, particularly for the younger age group to fit better, in particular by decreasing its width. This may require manufacturers and retail outlets to carry more than two sizes of helmets. It may also require development of some simple retail measuring maneuvers to assure fit is accurate, such as use of a head caliper and comparison with the known helmet width.

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1 Thompson RS, Rivara FP, Thompson DC. A case-control study of the effectiveness of bicycle safety helmets. *N Engl J Med* 1989;**320**:1361–7.
2 Thompson DC, Rivara FP, Thompson RS. Effectiveness of bicycle safety helmets in preventing head injuries. A case-control study. *JAMA* 1996;**276**:1968–73.
3 Thomas S, Acton C, Nixon J, *et al*. Effectiveness of bicycle helmets in preventing head injury in children: a case-control study. *BMJ* 1994;**308**:173–6.
4 McDermott FT, Lane JC, Brazenor GA, *et al*. The effectiveness of bicycle helmets: a study of 1710 casualties. *J Trauma* 1993;**34**:834–45.
5 Maimaris C, Summers CL, Browning C, *et al*. Injury patterns in cyclists attending an accident and emergency department: a comparison of helmet wearers and non-wearers. *BMJ* 1994;**308**:1537–40.
6 Henderson M. *The effectiveness of bicycle helmets—a review.* New South Wales, Australia: Motor Accidents Authority of NSW, 1996.
7 Clarren SK. Plaquiocephaly and torticolis: etiology, natural history, and helmet treatment. *J Pediatr* 1981;**98**:92–5.
8 Bradtmiller B, Kristensen S. *The development of a 3-D data base of head and facial anthropometry for children and youth*. Yellow Springs, OH: Anthropology Research Project Inc, February 1995.