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Title and Subtitle: HELMETS FOR CHILD BICYCLISTS
SOME BIOMEDICAL CONSIDERATIONS

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Abstract:

The epidemiology of bicycle crashes identifies helmets as a major countermeasure, especially for children. Head impact tolerance, impact site, need for penetration resistance and sizing are reviewed, but not heat dissipation, though it is an important user consideration. A separate class of helmet for very young children is recommended. Current helmets are deficient in small sizes.

KEYWORDS: Bicycle accidents, children, head injuries, helmets, impact tolerance, anthropometry

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SUMMARY

Increased popularity of bicycling has led to more bicycle crashes. As a transport vehicle, the bicycle is somewhat less safe than a car but a good deal safer than a motorcycle. Bicyclists in an age range centred on age 12 contribute most casualties, but young riders, about age 6, have a high involvement rate.

Since head injuries constitute a large fraction of all bicyclist injuries and because of the disabling consequences of severe head injuries, the protective helmet is an attractive countermeasure. There is evidence for its effectiveness. This paper discusses certain bio-medical issues related to helmet specification and design, excluding ventilation.

In efforts to improve the protection afforded by helmets, a central issue is the tolerance of the head to impacts. While much progress has been made in recent years by theoretical and experimental studies, including mathematical modelling, no new tolerance criterion has been generally accepted. Empirical evidence, however, points to a substantial lowering of the peak acceleration limit of current test procedures and a further lowering for helmets for children under age six.

Other evidence, from field observations, suggests extension of the protected area, but raises doubts as to the need for resistance to penetration.

Good helmet fit is needed for comfort, stability and helmet retention. Few Australian anthropometric data of relevance are available, but it is likely that dimensions from American or European sources are applicable. Helmet models on the market seem deficient at the small end of the size range. A separate helmet specification is suggested for children of about five and under.

CONTENTS

INTRODUCTION

In 1975, the Standards Association of Australia formed Committee CS/14 to draft a standard for bicyclists' helmets later extended to include horse riding and similar activities. AS 2063 was published in 1977, based on AS 1698 (helmets for motorcyclists), with somewhat reduced performance requirements. In 1982 a revised edition of AS 2063 was published and the test methods were placed in a separate standard, AS 2512.

In 1985, the Committee agreed to prepare special requirements for bicyclists as distinct from other helmet users. The subcommittee appointed has prepared a new standard to resolve immediate problems, with a further major revision planned for the future.

This report is intended to consider two properties of helmets for bicyclists - degree of protection and fit - in the light of needs of children. Reference is made to salient papers and it has not been possible to avoid retracing some of the ground covered by Corner, Costello and Whitney (1985) in their comprehensive summary of the literature of injury tolerance and protection.

The tentative conclusions should be considered in the light of the outcome of investigations now in progress.

BACKGROUND

In the recent past, in this country, as elsewhere, bicycle riding has become increasingly popular. It has been promoted as an economical, and healthy, means of personal transport over urban distances. A number of Australian cities have developed "Bike plans", and bicycling, and especially its safety, has become the concern of community organizations and parliamentary committees.

With increased exposure have come more crashes. The full extent of injury from bicycle crashes is uncertain because they are notoriously under-reported. Of 139 bicyclists admitted to or treated at hospitals in the Sydney Metropolitan Region (Gonski, Southcombe and Cohen, 1979) only three seem to have been officially reported.

The number of casualties recognized depends on the source of data. Aggregated hospital contacts or discharges capture many more than police reports or accident claims. Mortality records are the most reliable source of bicyclist fatalities.

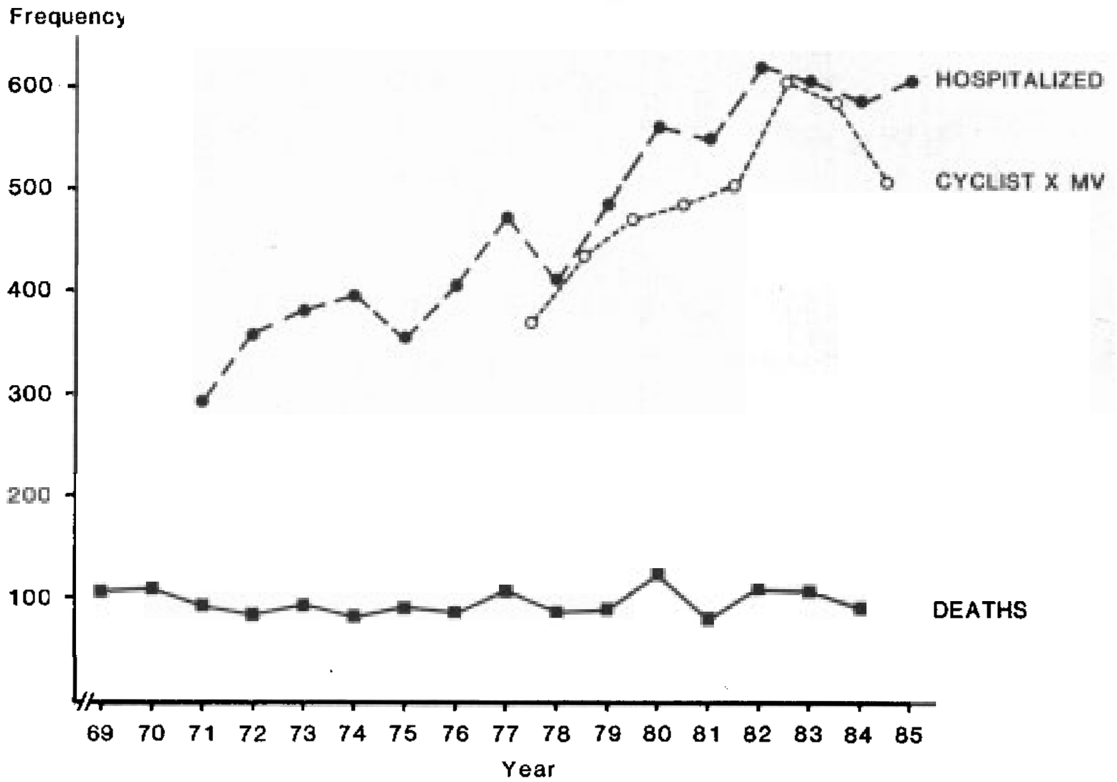

Fig 1 Pedal cyclist casualties

- ■ Deaths, Australia (ABS, 1986a)
- o Non-fatal, cycle x m.v., MAB claims, Victoria
- • Hospital discharges, W.A.

Fig 1 shows casualty frequencies, by year, from three sources. In addition to the 600 or so admitted to hospital in West Australia in recent years, it is estimated (Perth Bikeplan Study Team, 1985) that a further 9,000 require some form of medical treatment. According to an ABS survey (1985), in one year 6.326 persons in the city of Adelaide sustained injuries requiring medical treatment as the result of bicycle crashes.

It seems reasonable to make comparisons across state boundaries, as statistics derived from hospital admissions in ACT (Whateley, 1985) are very similar to those from Western Australia. Indeed bicycle accidents do not seem to differ much from Norway (Björnstig and Näslund, 1984), to New Zealand (Sage et al, 1985).

The steady rise in hospital admissions shown in Fig 1, is in contrast to the stationary death frequency, with Victorian claims (for injuries in cycle/motor vehicle collisions) intermediate but closer to hospital admissions. This suggests that whatever countermeasures or other mechanisms have been at work in the recent past have differentially influenced the most severe crashes. A graph in a bulletin of the Geelong Bikeplan (1980) shows an estimated death rate (per 10^5 cycles) falling from 17 to 1964 to 6 in 1976. This may be a process analogous to the fall in motor vehicle deaths per 10^4 vehicles with increase in motorization.

SAFETY OF THE VEHICLE

Where the safety of various transport modes is being compared, distance is the appropriate measure of exposure, as distance is transportations "product"; for recreational activities time is the appropriate measure. Wigan's (1983) analysis of bicycle ownership and use data, for Melbourne, suggests that the bicycle is largely used as a transport vehicle. The position of the bicyclist in relation to the car driver has been estimated by Mathieson (1986) as follows: fatalities per 10^8 km, car drivers 2, bicyclists 2.7 to 5.4. To put these rates in perspective, they should be compared with other modes of transport, as shown in Table 1.

TABLE I - Fatality rate per 10^8 passenger or occupant-km (Lane, 1977)

Rail	0.06	US, 1962-64
Airline	0.06	Australia, 1968-72
		US, 1968-72
Longhaul Bus	0.11	US, 1962-64
Tram	0.24	Melbourne, 1963-68
Urban Bus	0.33	Melbourne, 1963-68
Passenger Car	1.81	Australia, 1963-68
Horse-drawn transport	6-13	California, 1909
General Aviation	10	Australia, 1969-70
Motorcycle	22	Australia, 1971

Some of the rates in Table I, notably airline, car and motorcycle have decreased since the dates shown. (The rates estimated by Mathieson are for car drivers rather than car occupants). Evidently the safety record of bicycles is somewhat poorer than that of passenger cars, but much better than that of motorcycles.

AGE OF CASUALTIES

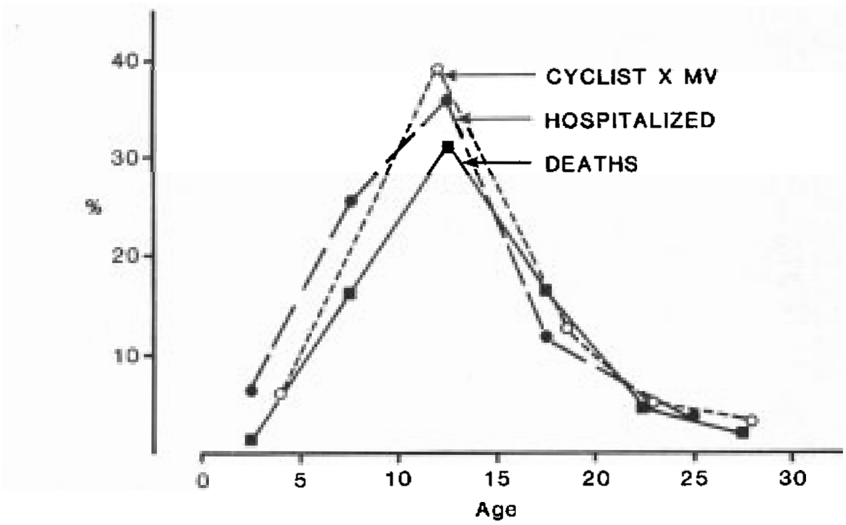

Fig 2 Age distribution of casualties as percentage of all casualties in each category (all distributions are truncated).

- ■ Deaths, Australia
- o Non-fatal, cycle x m.v., MAB claims, Victoria
- • Hospital Discharges WA.

In Fig 2, the age distribution of casualties shows a slight shift towards lower age as the collection moves from death to hospital admissions. The 10 to 14 years class accounts for 31% of total deaths and 36% of hospital admissions for accident claims, the wider class, 8 to 16 years, accounts for 61%. All three distributions have a common mode centred on age 12.

The hospital-contact series of McFarlane, Jones and Lawson (1982) had a modal frequency in the 10-14 age class, but in Gonski, Southcombe and Cohen's series of hospital admissions, the peak incidence was at age eight.

The microstructure of child accidents, concealed in the age classification of Fig 2, is revealed by Armson and Pollard's (1986) study of child cyclists requiring treatment at a single suburban hospital. The casualties are enumerated by single year of age, and the percentage, for each year, of children who regularly rode bicycles on the roads was estimated by questionnaire. (These percentages, 19% at 5, 11% at 6, 42% at 7 ......, are naturally much lower than for simple bicycle ownership, as estimated for Adelaide by ABS, 1985).

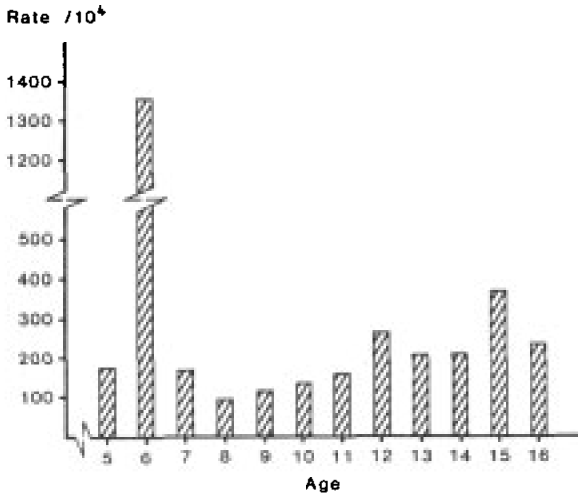

Fig 3 Relative crash rate per 10^4 child cyclists. Population, ABS (1986b). $X^2 = 29.9$, $.001 < p < .01$. (Rate is not quite an annual rate, as the survey ran from February through October, 1983).

Since the local government area **studied possesses the** epidemiological virtue of having much of its perimeter bounded by water, it may be permissable to use population data to compute rates. The 1981 population (ABS, 1986b) is used as proxy for 1983. In Fig 3, the high accident rate for children aged 6 is striking. This may be partly an artifact of the low percentage said to be riding, 11% for age 6, but even if a more likely percentage is taken, the 6-year rate is still very high.

Overall, the age range centred on age 12 is especially worthy of attention because of the high frequency of casualties it produces, as is another group, around age six, because of its high involvement rate.

BICYCLIST INJURIES:

There is a substantial consistency in the age, sex and severity distribution of injuries reported from different sources and different countries. Where there are differences, they reflect differences in data capture - for reasons referred to earlier.

McDermott and Klug (1984) analysed records from four Melbourne hospitals, the Motor Accident Board and the Road Traffic Authority - 431 male and 81 female bicyclists. Because of the sampling method, these were largely cases of severe injury. The age distribution was: less than 10 years, 22.9%; 10-16, 45.9%; 17-25, 19.5% and over 25, 11.7%. Head injuries occurred in 58.8%, more frequently (and more severely) in those under 17 years.

Most of McDermott and Klug's bicyclists had been involved in a collision with another vehicle. But WA hospital discharge data show that head injury is the predominant type even in bicycle-only crashes (Fig 4). Head injury cases comprised 46% of bicyclists admitted to hospital in ACT. Intracranial injury, with or without skull fracture, accounted for 87% of bicyclist deaths in WA, 1971-1980.

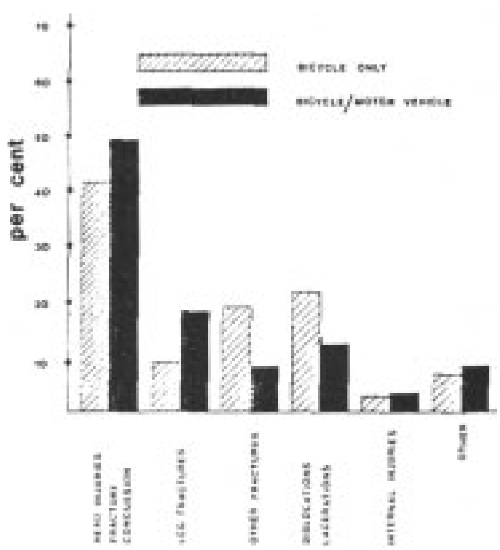

Fig 4 Bicyclists' injuries, by injury type.

Source: Western Australian Health Statistics.
Bar diagram from Perth Bikeplan Study Team

An earlier collection (McDermott and Klug, 1982) provides the relative frequencies of clinical subdivisions of head injury, as in Table II.

TABLE II - Types of head injury in pedal cyclists casualties

Type of injury	Cyclists	
	All (805)	With serious head injury as sole injury (170)
	%	%
Skull fractures	10	25
Facial fractures	4	13
Concussion	11	22
Cerebral laceration	5	2
Subdural, sub-arachnoid, extra-dural haemorrhage	1	3
Other, or intra-cranial	9	25
Lacerations	34	

Data from Zurich (Walz, Dubas, Burkhart and Kosik, 1985), based on police records, show the distribution of head injury severity in bicyclists and moped riders in terms of the Abbreviated Injury Scale (Fig 5). The more severe head injuries (AIS 3 to 6) constituted 23% of all head injuries.

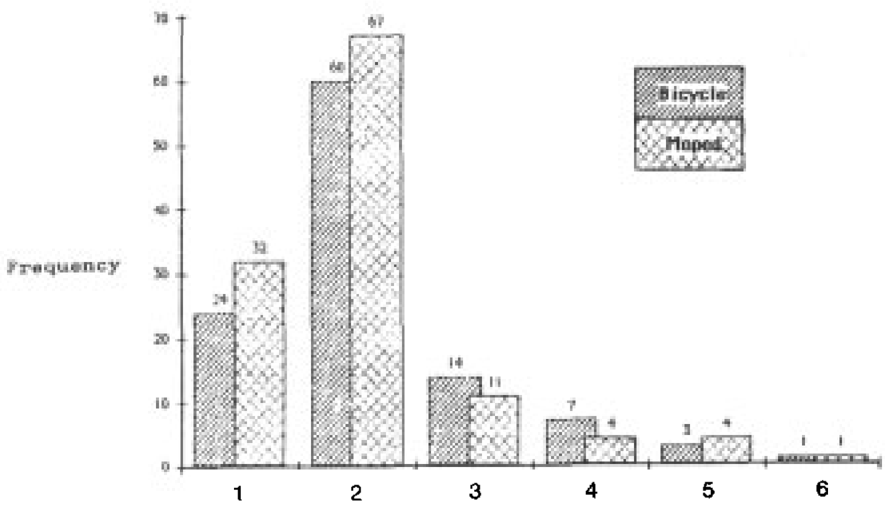

Fig 5 Head-AIS in light two-wheeler casualties.
Source: Walz et al.

Head Injuries

The head injury of bicycle crashes (and, generally, of vehicle accidents) is the "closed" head injury. The cranium may be fractured, but is not penetrated.

Head injuries can be classified also by their location, from outside in: thus, scalp, skull, extracerebral bleeding, intracerebral bleeding and brain tissue damage; or as to direct relation to the impact site or more remotely, due to momentary pressure changes or translational or angular acceleration. These processes may, or may not, cause haemorrhage in relation to layers of brain coverings, or damage may be caused directly to the neural tissue, particularly nerve fibres, as in diffuse axonal injury.

The clinical syndrome of "concussion" is frequent (Table II). It may occur without skull fracture or blood vessel damage. It is not defined precisely but includes a period of unconsciousness with or without loss of memory for events immediately preceding the impact, and with or without residual effects. It is now considered to be due to functional or, if more severe, structural damage to nerve fibres (Ommaya, 1985; Blumbergs, 1986). According to Ommaya, the essential element is inertial loading to the head, produced by a head impact or by rotational acceleration without head impact.

As the magnitude of acceleration increases there is, Ommaya suggests, a progressive extension of critical strain from the surface towards the centre of the brain, the strain producing functional disconnection of elements of the brain. Clinical "concussion" is in the middle of this range of severity.

In summary, a large part of the injury pattern is comprised of head injuries, with or without (in one fifth of cases) injuries to other body areas.

THE HELMET AS A COUNTERMEASURE

EFFECTIVENESS

The effectiveness of a law requiring motorcyclists to wear helmets was demonstrated by Foldvary and Lane (1964). The helmets of the time, which would now be considered of inferior performance, achieved a 30% reduction in risk of fatality. A reduction factor for head injury (of any degree) of 33% was obtained for the years 1954 and 1955, by Chandler and Thompson (1957). A reduction factor of 43%, with the improved helmets of the 70's, can be derived from the increased deaths after the repeal of helmet wearing laws in USA (Watson, Zador and Wilks, 1980).

Dorsch, Woodward and Somers (1984) showed that wearing a "good" helmet made a large reduction in head injury in bicycle riders involved in crashes. The reduction factor for fatality was estimated at 95%, but this figure was derived from much arithmetical manipulation of the original data. Nevertheless, it is reasonable to expect a higher head injury reduction factor for cyclists than for motorcyclists because of the usually lower head impact velocities, as illustrated in Fig 6. At high velocities, the impact will be non-survivable with or without a helmet, while at very low velocities, no injury is sustained with or without a helmet. The maximum is attained at velocity for which the helmet is optimised (a point which will arise later).

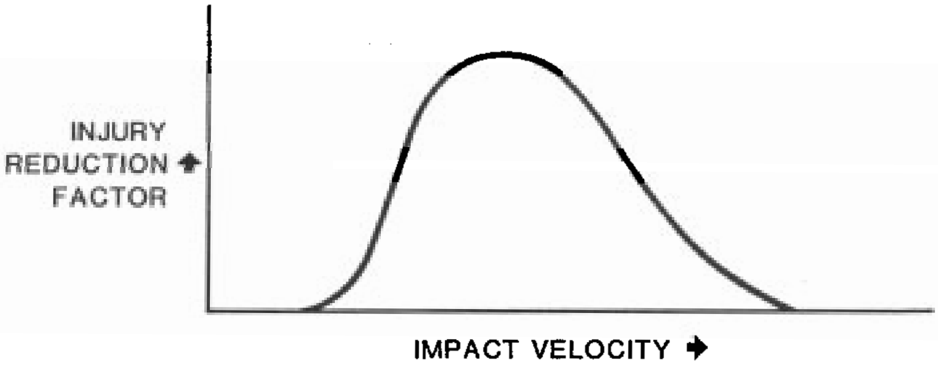

Fig 6 Hypothetical relation of injury reduction by helmets, to head impact velocity.

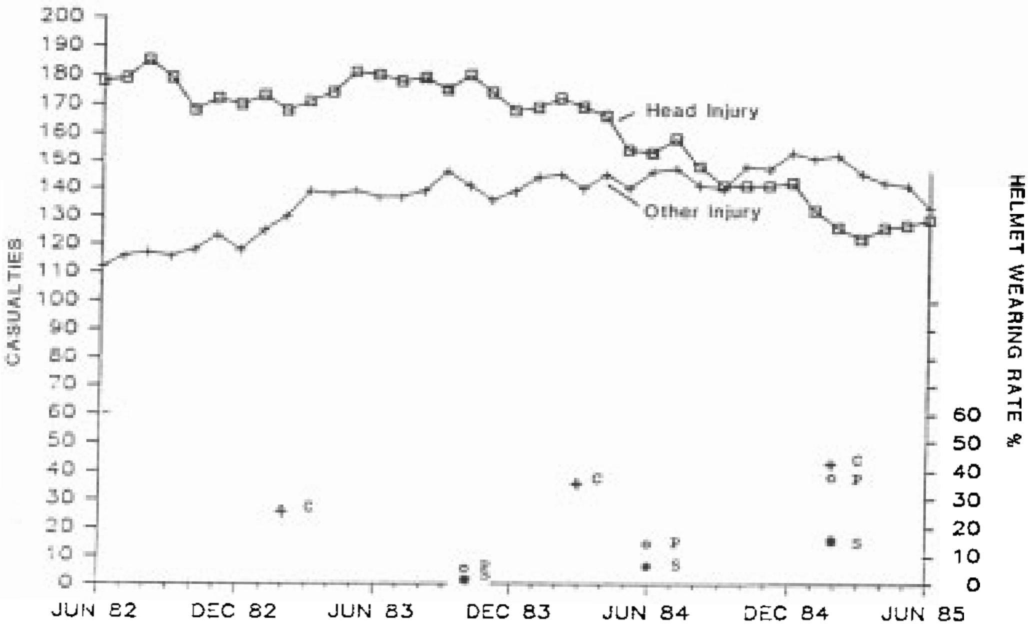

Fig 7 Bicyclists killed or hospitalised, Victoria (modified from Wood, 1985). P, primary school children; S, secondary school children; C, adult commuters.

In Victoria, campaigns have achieved a substantial rise in wearing rates by cyclists between 1983 and 1986: from 5% to 58% in primary school children, from 2% to 18% in secondary school chidren and from 26% to 44% in adults (Wood, 1986). Fig 7 (taken from Wood) shows a fall in bicyclist casualties with head injuries over the period of the campaigns, with little change in casualties with other than head injury. While this does not constitute a formal evaluation, it is very suggestive that the observed reduction in casualties with head injuries is a consequence of increased helmet wearing.

Mathieson has considered the benefits of various countermeasures and finds that the largest benefit would be from a 50% increment in helmet wearing (from 25% to 75%), which, he estimates, would yield about $9M annually. The cost is not estimated, but the attractively large saving indicates the desirability of increasing the wearing of good quality helmets.

HEAD IMPACT TOLERANCE

According to Newman (1978) design requirements for helmets can be classified as "functional", which ensure that the helmet "works", and "non-functional", which make it usable. Newman's first class includes shock attenuation, penetration resistance, abrasion resistance, retention capability and overall reliability; his second includes cost, aesthetics, comfort, weight and thermal properties.

Another criterion might be added to the first class, namely, "fit", since it contributes to retention capability as well as comfort. Others, again, could be added - such as resistance to weathering (Sarrailhe, 1984).

Besides the property of protecting the head from abrasion, the shell and liner are intended to "spread the load", that is to increase the area of head surface exposed to the force applied by the impacting surface or object, and also to reduce the magnitude of the force applied. It is the last objective which is the essence of helmet specifications.

Rotation

It has been recognised since the work of Holbourn (1943) that rotational acceleration of the head plays a major part in brain injury. For a particular, though common, venous haemorrhage ("gliding contusion")

Löwenhielm suggests a threshold of 4,500 rad/s^2 together with a velocity change of 70 rad/s. Ommaya (1985) proposes a relation between angular acceleration and AIS, shown in Table III.

It is to be noted that Aldman (1976) has measured angular accelerations in excess of 4500 rad/s^2 in helmeted dummies dropped from one metre on to simulated road surfaces at speeds up to 50 km/h.

TABLE III Head angular acceleration and predicted AIS (Ommaya, 1985)

Acceleration (rad/s^2)	Angular velocity (rad/s)	
	<30	>30
<1700	AIS 0,1	AIS 2
1700-3000	"	3
3000-3900	"	4
3900-4500	"	5
>4500	AIS 5	

Since there is no direct means of damping rotational acceleration, it does not enter the standards in terms of numerical values in a test procedure. It is obvious, however, that for an oblique blow, the properties of a helmet may reduce the tangential force acting on the head.

This process is taken into account by requiring the helmet shell to be smooth (i.e. with low friction) and projections to be limited in height and, if possible, faired, so as not to engage in surface or objects contacted which would impart rotation to the helmeted head. Clearly it is advisable to avoid overhang at edges.

Translational Acceleration

Providing an effective device to protect the head against impact began empirically, but efficient design demands numerical values in physical units to indicate the level at which external protection must begin. This is the basis of the search, still unfinished, for a "tolerance level", below which the head suffers no more than a specified injury or no injury.

Apart from such obvious influential variables as age (to be discussed later), sex, direction of blow, there are other points to be considered. What degree of injury (if any) can be accepted? Should it be momentary disturbance of the electro-encephalogram (as in the instrumented footballers of Reid et al, 1975) or injury just short of fatal? In addition, where should the tolerance value be located on a hypothetical dosage-response curve, supposing one could be constructed.

Finally, severity of injury and severity of outcome tend to be confounded, notably at the upper end of the age range. Whether young children are more or less fragile than young adults is not altogether clear, though often assumed.

In practice, the difficulties of real-life data collection, obvious limitations on experimentation, not to mention the complexities of the head as a physical system, all tend towards lumping these variables and adopting a single global figure for "tolerance".

A numerical estimate of tolerance to impact is an evidently necessary basis for design of protective devices. One such estimate is the so-called Wayne State Tolerance curve (Patrick, Lissner and Gurdjian, 1965). It is similar to but not identical with that proposed by Gurdjian, Lissner and Patrick in 1962.

At least five tolerance indices have been derived from WSTC, including the Gadd Severity Index and the Head Injury Criterion (HIC), the latter being used in certain safety specifications for motor vehicles (McElhaney et al, 1973).

In WSTC, the estimate of tolerance is presented as a smooth curve, without associated data points. Acceleration here is "Effective Acceleration which is based on a modified triangular pulse, in which the effective acceleration is somewhat greater than half the peak value". The highest point on WSTC is 230 g at 2 ms duration and is presumably the origin of the 400 g peak used in a number of helmet standards.

The injury criterion is said to be "reversible concussion with no after effects", though the physical criterion was the production of linear skull fractures in a cadaver. The WSTC was, in fact, derived from several sources (Gibson, McLean and McCaul, 1984). Over the past twenty years, the WSTC and derivatives have come under considerable criticism (for example, Newman, 1975, 1980).

In recent years there has been a good deal of work, experimental and theoretical, with emphasis on construction and validation of mathematical models. Several are briefly summarised below.

Ward and Nahum (1979) compared mathematical model predictions with cadaver tests and impacts on helmeted headforms (matching known accidents) Intracranial pressure was a determining factor, pressure over 34 psi (234 kPa) being associated with injury. (This is not far from the 40 psi of Gurdjian, Lissner and Patrick, 1962).

Kikuchi, Ono and Nakamura (1982) have proposed tolerance curves, derived by dimensional analysis from primate experiments, of the same general shape as the WSTC. The acceleration variable differs from that of WSTC, being the magnitude of a square wave yielding the same change in velocity as in the experimental impact. The injury criteria were "concussion", as defined by the authors, and vascular damage. The concussion threshold was sometimes higher than that for haemorrhage. Generally tolerance to lateral impacts was higher than that for frontal or occipital.

Stalnaker, Lin and Guenther (1985) have also used dimensional analysis to deduce human tolerance from primate experiments. Their New Mean Strain Criterion (NMSC) has been determined for three directions of impact and is said to predict the severity of head injury on the AIS scale. (The strain is defined as the displacement of one side of the cranium with respect to the other, divided by the cranial breadth).

For a given impact, the order from most to least injurious response is L-R, A-P, P-A and S-I. (This is contrary to the views of Kikuchi et al, above, but Hodgson et al (1983) show that equal energy impacts produce higher forces and accelerations in lateral impacts).

In determining the NMS, the test headform must have a human-like impact response. (The Hodgson-WSU headform used for testing American footballers' helmets is described by Corner et al).

The outputs from the triaxial accelerometers, after processing, are entered into a set of algorithms which yield peak force, Mean Strain and predicted AIS.

Ommaya proposes that two criteria for brain injury should be used "in tandem" according to the following plan. For contact impacts and translational acceleration, MSC should be used; for rotational accelerations, the criterion is to be selected from Table III.

Despite this and other research, there has not so far been a reconciliation of outcomes leading to a new, agreed head injury threshold.

It is therefore reasonable to look to real-life events including the effectiveness of equipment built to WSTC-based standards.

The Head Injury Criterion has an acceptance value of 1000. Jones and Mohan (1984) found that baseballers struck by a "fastball" sustained impacts of about this HIC value but received injuries up to fatal in severity.

Morfey (1986) has reanalysed three series of survived and fatal falls from high bridges and calculated the acceleration of the head on entry to the water. He concluded that 50% of subjects would suffer brain damage at a peak acceleration of 205 g and HIC of 570.

Slobodnik (1979) collected military aviators' helmets (designed to meet ANSI Z-90 test methods, i.e. based on WSTC), whose wearers had been in accidents. Fourteen helmets were selected which had experienced a single, non-glancing blow. The accident-helmet damage was matched by repeated tests on new components. The head form used was the Hodgson-WSU headform designed to simulate the physical properties of the head. It was found that head injury cases were associated with peak accelerations below the 400 g maximum specified. In the eight cases with head injury, the liner compression was not complete. Slobodnik concluded that the peak acceleration should not exceed 150 g. It should be noted that this level was recommended to avoid temporary incapacitation that would impede escape from a crashed helicopter.

Tolerance of Children

The above discussion relates to impacts to human heads in general, but practically, to adults.

Information regarding the head impact tolerance of children is scanty, though it is usual for authors to draw attention to the structural differences between adult and child skulls.

Burdi et al (1969) have described the relative sizes and rates of growth of body parts of children, drawing attention to the relatively large head of young children and weak supporting neck structures. Seventy percent of the adult brain weight is reached at 18 months, 80% at three years, 90% at 5 to 8 years and 95% at the 10th year. The infant skull is pliable which, according to these authors, makes the child's head less resistant to impact trauma.

Snyder (1969) has analysed fourteen well-documented cases of head-first impacts of children, from a large collection of accounts of free-fall accidents. Thirteen were impacts on to hard surfaces with velocities from 29 to 64 ft/s (8.8 to 19.5 m/s). All but two suffered severe head injuries, fatal in one case. One two year old who fell 25 ft (7.6 m) into snow suffered no injuries. According to Snyder, these cases represent upper limits of free-fall survival.

Estimates of acceleration were not attempted in this paper but Mohan, Bowman, Snyder and Faust (1979) have investigated 30 cases of head-first free-falls of children, from one to ten years old, six by computer simulation. Falls from as low as 2 m can cause skull fractures[a] and concussion. Acceleration parameters correlated better with injury severity than energy-based measures. Injury tolerance limits were estimated to be 150-200 g for 3 ms average accelerations and 200-250 for peak values.

Fayon and Tarrière (1974), by dimensional analysis of data from animal experiments reported by others, conclude that the head impact tolerance of a child aged 6 is close to that of an adult: that of a child aged 3 is substantially less

SOME HELMET SPECIFICATION ISSUES

THE LINER

Several descriptions are available of the mechanics of the helmet shell and liner (for example, Rayne and Maslen, 1969; Newman, 1978). The function of the liner is to be crushed, ideally at constant applied force, and so limit the force applied to the surface of the head.

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a To this list could be added another case, the writer's own. At the age of about seven, he fell head-first through 2.2 m on to a concrete surface. He was not unconscious and sustained no lasting sequelae, apart from a then undiagnosed, depressed fracture of the skull. He has a clear recollection of events immediately preceding and following the impact, even after 60 years.

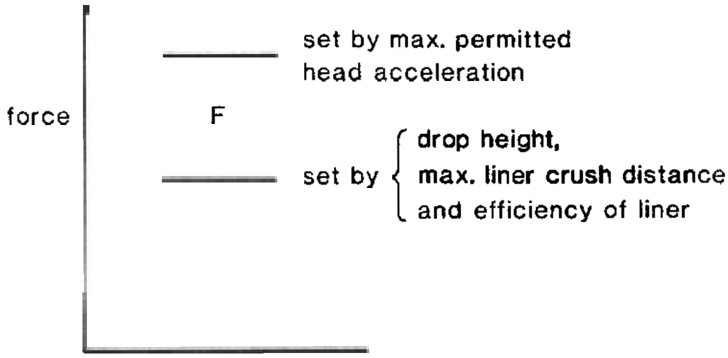

Fig 8 F, the force on the liner (and on the head) must lie between the limits shown, (drop height is that specified in the standard).

The upper boundary of the crushing force on the liner (and of the head) is set by the maximum permitted acceleration of the head form and by its mass (Sarrailhe, 1984). The lower boundary is effectively set by the impact velocity (drop height), required in the standard, the energy-absorbing efficiency of the liner and the available crushing thickness, since the impact energy must be matched by the average force and depth of crush (Fig 8).

In a given impact which results in head injury above the criterion level of injury (whatever may be chosen, including no injury), any crushable thickness in the liner that is not used up is, in effect, wasted.

In eight of Slobodnik's cases with head injury, the liner compression was not complete. Hurt, Ouellet and Thom (1981) measured the depth of crush in 216 motorcyclists' helmets: it was less than 2.5 mm in 86%. Newman (1984) has pointed out that some of the actual crush distance is restored within a short time after the impact, so that the amount of crush may be under-estimated. An experienced investigator should, however, be able to see and feel whether any appreciable crush at all has occurred.

For a given impact, maximum protection would be achieved if the liner just reached its maximum compression. It is obvious that this protective effect cannot be optimised over the range of impact velocities. Since this range is indeterminate upwards, an explicit decision must be made (by specification writers) about a suitable cut-off and this implies a decision that the most severe injuries cannot be catered for.

This is as much an operational as a biomedical problem. The object is to maximise "benefit" to the entire population of bicyclists involved in accidents , where benefit might be the absence of head injury other than minor. It is possible that there may eventually be sufficient data, which must include distributions of severity of injury in helmeted bicyclists, to permit a computation of this kind.

Despite the view of Walfisch et al (1981) that an HIC of 1500 is acceptable, as implying less than 50% probability of "cerebral injury", a more general opinion is typified by Hodgson's, that "concussion" is a conservative end-point for the design of head protection. It is not possible to assign a precise AIS score to this, but it appears to be between AIS 2 and 3.

On present information, the conclusion to be drawn from the above discussion and the preceding section is that the permitted headform acceleration should be substantially reduced (Corner et al suggest 200 g), and that the test headform should have "humanoid" physical properties.

In helmets designed for children under 5, the maximum acceleration should be set even lower, and this ought to be the dominating consideration in the design of helmets for these children.

THE PROTECTED AREA

The location of impacts on the head has been recorded by a number of investigators. Walz et al (1985) give impact locations for injuries ≥ AIS 1 and for ≥ AIS 2 for a mixed population of moped and bicycle riders. Stöcker and Löffelholz (1984) reproduce diagrams from an unpublished paper of Schüller et al. concerning riders of "powered two-wheelers".

Mohan et al (1984) have reported on the location of superficial head injuries and of helmet damage in cases of "motorised two-wheelers" admitted to a neuro-surgery ward. They specifically refer to impact below the level of the liner.

Otte, Jessl and Suren (1984) indicate the location of soft tissue injuries, skull fractures and helmet impact points in injured motorcyclists. Krantz (1985), for a series of fatally-injured motorcycle and moped riders, reports rather more impacts on the parietal and occipital region than in the other groups. He refers to most impacts being in "the hat-band area".

From a review of motorcyclist casualties, Harms (1984) notes that "the principal points of impact fall within a band across the front to the other side. Very few contacts were made to the back of the head and ..... only one .... to the top".

In this impressive array of observations, there is general agreement. The face, frontal and temporal areas are frequently struck; the occipital region much less frequently and the vertex rarely. These observations have obvious implications for the location of ventilation apertures.

While the impact locations charted cannot be directly overlaid on the diagrams given in the Australian Standard (SAA 1984), it appears that there are areas in the temporal region, with a high impact frequency, which is outside (below) the test area, that is the area required to have an energy-absorbing property.

THE IMPACTED OBJECT

Another aspect of the helmet which is also as much operational as biomedical, concerns the nature of the impacted surface and its relation to test procedures.

According to McLean (1981) in 80% of bicycle crashes the surface impacted by the rider's head is the road. In a series of 173 fatally injured bicyclists (Fife et al., 1983) "nearly all the serious head injuries came from blunt surfaces".

In a series of 617 motor cycle crashes, Sniveley (1978) recorded only one case of helmet penetration - by a propellor blade of a motor-boat! This is not to say that other helmets were not struck and not penetrated by "sharp objects". In the series of Harms, of 78 objects contacted most were surface or edges, with only 5 "other". No mention is made of penetrating objects.

Details of the shape of objects struck by the head of motorcycle or moped riders are given by Vallée et al. (1981). "Stiff" objects with a contact area of less than 200 mm^2 accounted for four cases of 263, and produced two AIS 2 and one AIS 3 injuries. Tests against a plane surface or an edge would, they say, match 95% of the impacts recorded. There were only three cases, of 293, of double impacts on the same head location.

These observations suggest that the penetration test called for by the current Australian Standard for cyclists' helmets may be redundant. There is a suggestion that a penetration requirement is design-restrictive to the detriment of other qualities (Glaister, 1982). There may also be some question as to the logic of requiring a test for penetration resistance when a substantial area of the shell is permitted to have zero resistance to penetration.

If it is thought desirable to have a general test for shell integrity, an impact against an edge seems appropriate.

It will be noted that the observations as to liner crush and nature of impacting surface have been made on motorcyclists' helmets, as have most on impact location. It is highly desirable that information of this kind be collected on bicyclists' helmets. A difficulty has been the low helmet-wearing rate of bicyclists - 2% in Göteberg (Kroon, Bunketorp and Romanus, 1984) and in school-children in Tucson (Weiss, 1986). The rate is understood to be low also in the Australian cities where current projects are in progress.

As regards relating injury to liner crush, it must be kept in mind that concussion may occur if rapid head rotation takes place even without much translational acceleration, and that individual helmet-makers may adopt more conservative, in-house acceleration limits than the standard requires.

FIT

Appropriate fit of a helmet, for the range of user sizes is obviously necessary for comfort and hence acceptability. Variations in hair quantity and style may increase the range of sizes slightly beyond that suggested by head dimensions. Good fit is necessary, too, for stability. In addition to this general requirement, fit in certain areas, such as the lower rear part of the helmet may contribute directly to helmet retention (Mills and Ward, 1985). Retention strap mechanics are discussed by Mills and Ward and by Marston and Mathieson (1986).

Finally, fit may need to be considered if additional areas of the head come to be required to have impact protection.

Relevant anthropometric information is evidently needed for efficient design, particularly in view of the desirability of limiting overall shell size.

ANTHROPOMETRY

Though there have been some well-conducted studies, the largest under military auspices, anthropometry for ergonomic purposes has not flourished in Australia. In consequence, it is usual for designers and other would-be users to make do with the data from USA or Europe. Surveys of dimensions of children have been mostly concerned with growth.

With regard to head dimensions, the National Health and Medical Research Council (1981) has published curves for, inter alia, head circumference (median and selected percentiles) for males and females up to age 16. The curves for height and mass are based on surveys of N.S.W. children (Jones, Hemphill and Meyers, 1973; Jones and Hemphill, 1974). Head circumferences for children under five are derived from this large survey, but those for children five to sixteen are taken from the compilation of Nellhaus (1968), consisting of "grand means and standard deviations" of data sets from U.S.A., Europe (mostly northwestern) and Japan. Nellhouse states that, "race causes no appreciable difference in head circumference in either sex" and, "head circumference measurements obtained largely before World War II are virtually identical" with those he compiled.[b]

More recent data are provided by a survey, specifically aimed at the needs of consumer products, by Snyder, Spencer, Owings et al. (1975). This compilation was based on measurements of just over 4000 children, representative of the U.S. population of children from 2 weeks to 13 years of age, and includes head length and breadth as well as circumference. Fortunately, the head circumferences are not very different

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[b]Vimpani, Penfold et al. (1985) have identified some 40 Australian anthropometric studies of children, of the past 25 years. Nine included head circumference, but do not appear to offer advances, for ergonomic purposes, on the data referred to above.

from those reproduced in the NH&MRC curves (see Appendix 1).

Snyder, Schneider, Owings et al. (1977) have extended these data to age 18, with a number of additional head measurements: bizygomatic, lower face height, tragion to back of head, tragion to top of head, ear sellion depth, bitragion breadth and nose length.

Another source, directly related to helmets, is a set of detailed specifications for headforms for use in helmet testing, issued as a draft by the International Standards Organisation in 1983. These specifications provide surface contours for the upper part of the head. They are not related to age, but the 15 headforms span circumferences from 640 mm to 500 mm (about a 50th percentile male aged three). The source of these dimensions is understood to be a Royal Air Force anthropometric survey of 1973.

HOW MANY SIZES?

A practical consideration for the helmet maker is the large cost of dies for the shell-moulding process, which puts a constraint on the number of shell sizes. In the limiting case of one size of shell, this would have to accommodate a liner sufficiently thick to meet the impact requirements and fit a 95% adult male. Consequently a good deal of space would have to be filled with comfort padding as well as the liner for a 5% female, of say, age five.

The situation is less difficult than appears at first sight since the growth of the head from about age four to adult is much smaller than for other body parts, as noted earlier. There are disadvantages, however, to the small wearer. In the limiting case cited, the shell being taken to be approximately hemispherical, the additional overhang (i.e. excess radius) is about 18 mm and the excess shell mass about 40% compared with a "tailor-made" helmet for a 5% female of five years. Some benefit accrues to the wearer with small head size, in that a thicker liner would provide more impact attentuation.

The range of helmet sizes might be expected to cater for a 5th percentile female aged six and a 99th percentile adult male, say 48.5 cm to 62 cm. While the high end of the range is well supplied, according to a survey in the bicycling magazine Freewheeling (May-June, 1985), the lower end is not. Only one helmet in eleven suitable models had a 49 cm size, the next larger being 51 cm. The deficiency is alleviated to some extent by some makers supplying soft pads, some in several thicknesses, which extend the fit of any size downward and provide for heads of unusual shape.

A survey summarised in the magazine Pedal Power (July, 1985) indicates that 9% to 24% of trial users (ages not given) were unable to obtain a satisfactory fit with the seven models tested.

It appears that problems can arise at point of sale as a result of lack of appropriate information and advice from the salesperson. This difficulty is exaggerated when helmets are sold in supermarkets, which are understood not to permit the display of a card giving the size range available. Information to purchasers ought to include, for example, the suggestion that those who are hard to fit should try alternative brands with the same nominal size.

VERY YOUNG CHILDREN

Despite the advice of various authorities, it is evident that quite young children ride bicycles in traffic. In addition, off-road riding contributes its share of trauma, and even younger children are carried as passengers by bicycling parents.

The curve of head growth is quite steep below age four. It therefore seems that there is a special age group that cannot readily be catered for by the school-child and adult range of helmet sizes. As noted earlier, it is probable that children below age six should have a numerically lower criterion for brain injury than older children and adults. Thus there is a case for a separate helmet for these young children with appropriate dimensions (see Appendix 1), and a lower peak acceleration on the impact test (150 g has been suggested).

ADDITIONAL DIMENSIONAL NEEDS?

There are particular areas of the head which may need attention in further helmet development. Mills and Ward have pointed to the suboccipital region as important in helmet retention and the lower temporal region may need to be assured of impact protection.

The similarity of Australian and U.S. circumferences up to age five, and the remarks of Nellhaus suggest that American dimensions may be reasonable proxy in the case of older children and adolescents. Confirmation would, of course, be desirable.

For other head dimensions of children, no Australian data appear to be available. Bizygomatic diameter is included in the compilation of Snyder et al (1977). Eighteen facial dimensions have been measured by Young (1966) for subjects from one month to 17 years, intended for use in oxygen mask design.[c] None of the surveys encountered gives a distribution of head length to breadth ratio, length and breadth being only weakly correlated.

Pang (1986) has suggested making use of magnetic resonance scanning to derive head dimensions. A Medline search has not discovered any published accounts of the use of NMR for this purpose. Should it prove technically feasible, the acquisition of a representative sample of undamaged subjects may not be without difficulty.

CONCLUSIONS

In terms of age distribution, bicyclists involved in crashes have a modal frequency at about age twelve. Younger cyclists appear to be at greater risk of injury-producing crash, with a peak at age six.

Head injury is a major component of bicyclists' injuries. Helmets have been demonstrated to be effective in reducing or preventing head injuries for bicyclists, as they have for motorcyclists.

There are possibilities for improvements in helmets:

In the absence of consensus for a new criterion for head impact tolerance, empirical evidence suggests reducing the present value of the peak acceleration (400g) on the impact test of the Australian Standard. The suggestion of Corner et al., 200 g. is reasonable. There is some evidence that this should be still lower (150g) for children under six years of age.

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c Regarding adults, mention should be made of the "standard" 50th percentile adult male head, with face and jaw, developed by Hubbard and McLeod (1973).

It may be advantageous to extend the impact-protective area below the present test line, in the temporal area.

The need for the present penetration test is doubtful.

The range of helmets at present available appears to be deficient in very small sizes.

There is a need for a separate standard for helmets for very small children, with reduced peak acceptable acceleration, and perhaps omission of the requirement for a hard shell.

There is a need for further information for the benefit of helmet design, standard drafting and promotion of helmet wearing.

Continued accident case collection, with recovery and examination of the helmet, including cases of little or no head injury, and recovery of information about helmet retention, nature of struck object and location of impact.

A further attempt to capture all injury-producing bicycle crashes for a defined population, with orientation to determining age-specific rates, by single year of age.

If an anthropometric survey of children is considered, it should be planned with due regard to sample size and representation, and proven methods of measurement.

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APPENDIX I

Head Circumference (cm)

Males

	Australia		U.S.A.				various
	Jones & Hemphill		Snyder 1975		Snyder 1977		Nellhaus
Age	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	50%**
1	46.0	1.57	46.0	1.3			47.0
2	49.17	1.60	49.4	1.6			49.3
3	50.07	1.53	50.4	1.1	50.2*	1.6	50.4
4	50.79	1.51	51.1	1.3	50.7	1.3	51.0
5	50.96	1.72	51.8	1.4	51.2	1.3	51.3
6			52.1	1.4	51.6	1.6	51.5
7			52.6	1.5	51.9	1.6	52.1
8			52.7	1.5	52.6	1.5	52.5
9			53.2	1.5	52.6	1.7	52.8
10			53.5	1.5	52.9	1.4	53.0
11			54.2	1.3	53.6	1.5	53.2
12			54.2	1.5	53.8	1.7	53.8
13			54.1	1.4	54.3	1.7	54.2
14					54.8	1.9	54.5
15					55.4	1.7	54.8
16					56.5	1.9	55.2
17					56.7	1.7	55.7
18					57.2	1.6	56.1

Females

	Australia		U.S.A.				various
	Jones & Hemphill		Snyder 1975		Snyder 1977		Nellhaus
Age	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	50%**
1	45.65	1.31	45.4	1.1			45.9
2	48.09	1.46	48.0	1.3			48.0
3	49.75	1.49	48.9	1.1	48.7*	1.5	49.2
4	49.69	1.40	50.0	1.5	49.7	1.4	50.0
5	49.98	1.41	50.5	1.3	50.2	1.5	50.2
6			51.0	1.5	50.5	1.4	50.5
7			51.2	1.2	51.1	1.5	51.3
8			51.5	1.3	51.8	1.6	51.6
9			52.2	1.3	52.0	1.6	51.9
10			52.3	1.4	52.7	1.7	52.1
11			52.8	1.3	52.8	1.9	52.7
12			53.2	1.4	53.1	1.6	53.0
13			54.1	1.5	53.7	1.8	53.3
14					54.0	1.5	54.0
15					54.3	1.8	54.3
16					54.2	1.6	54.5
17					54.6	1.6	54.8
18					54.3	1.4	55.0

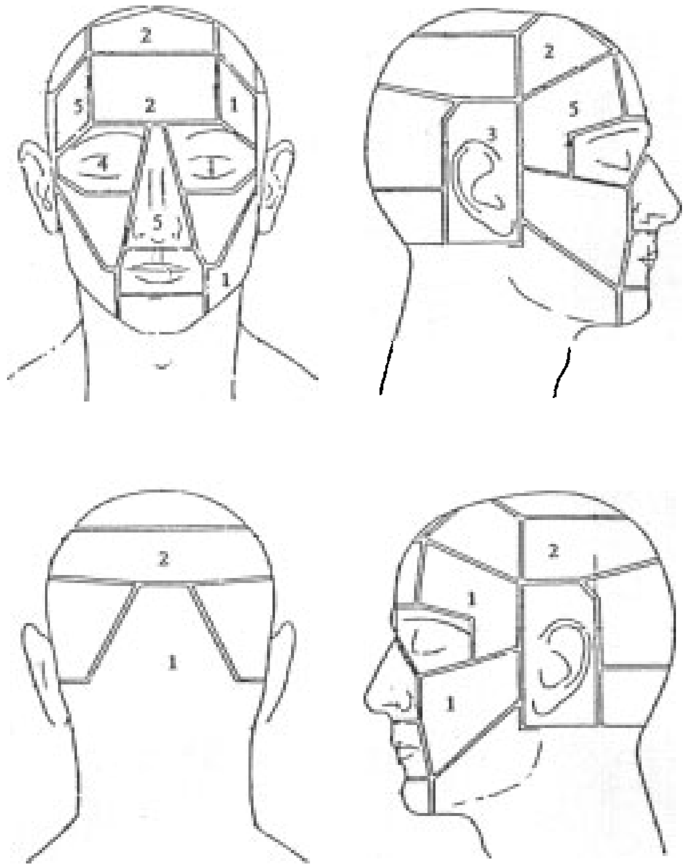
* age 2.0 to 3.5

** scaled from graphs

APPENDIX 2

Head Impact Locations

A



B

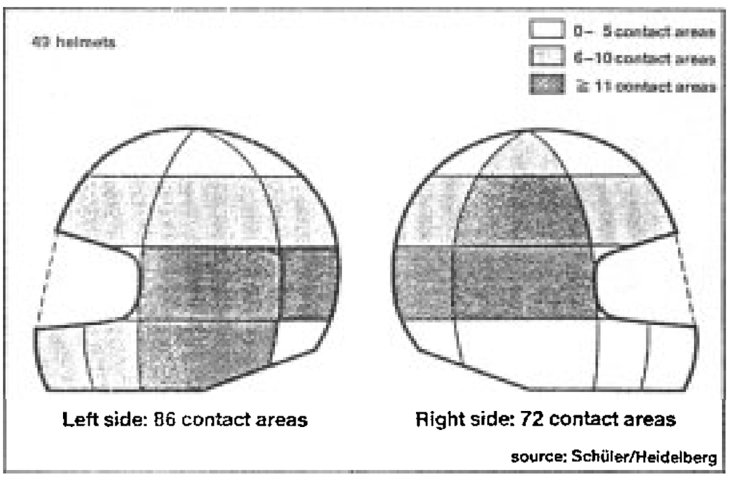
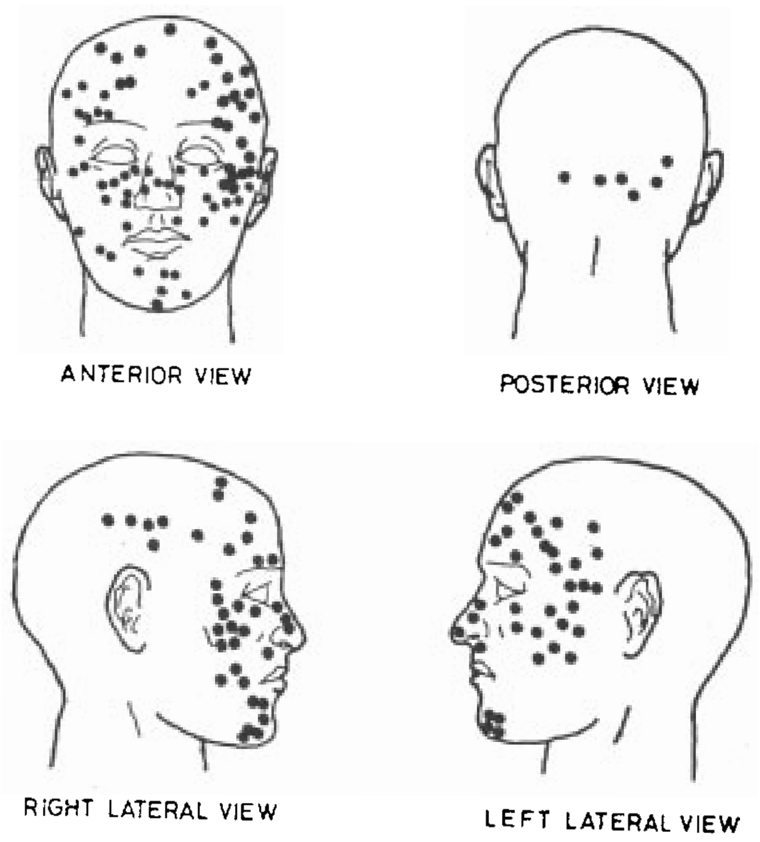
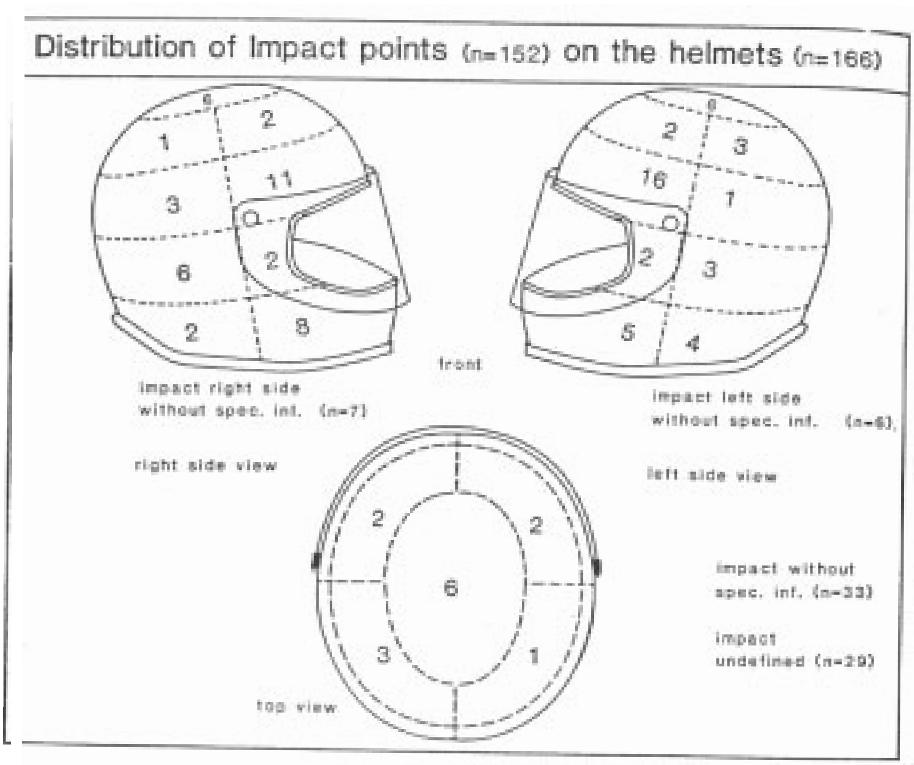


Fig. 9. A. Walz moped riders with head AIS ≥ 2
B. Schüler (cited by Stöcker & Löffelholz) 158 contacts, "powered two-wheelers".
C. Mohan et al (1984) Superficial injuries to unhelmeted two-wheeler riders.
D. Otte et al Impact points on 166 helmets of motorcyclists
E. Krantz Motor cycle and moped riders, 76 with & 23 without helmets.
F. Robertson et al (1966) motorcycle riders.

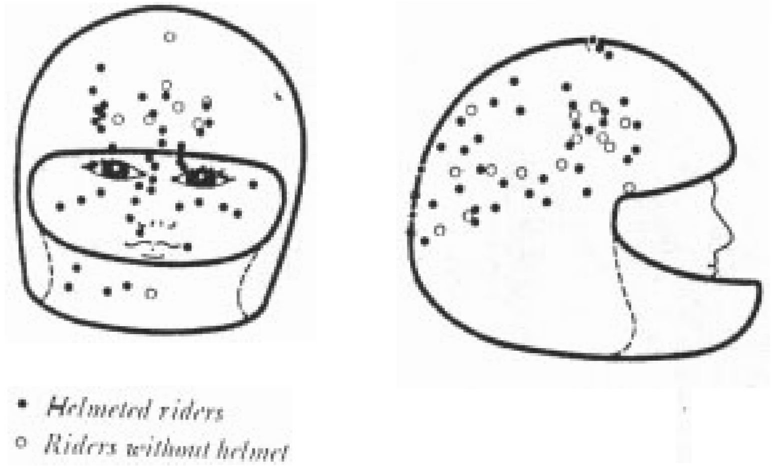
C


ANTERIOR VIEW
POSTERIOR VIEW
RIGHT LATERAL VIEW
LEFT LATERAL VIEW

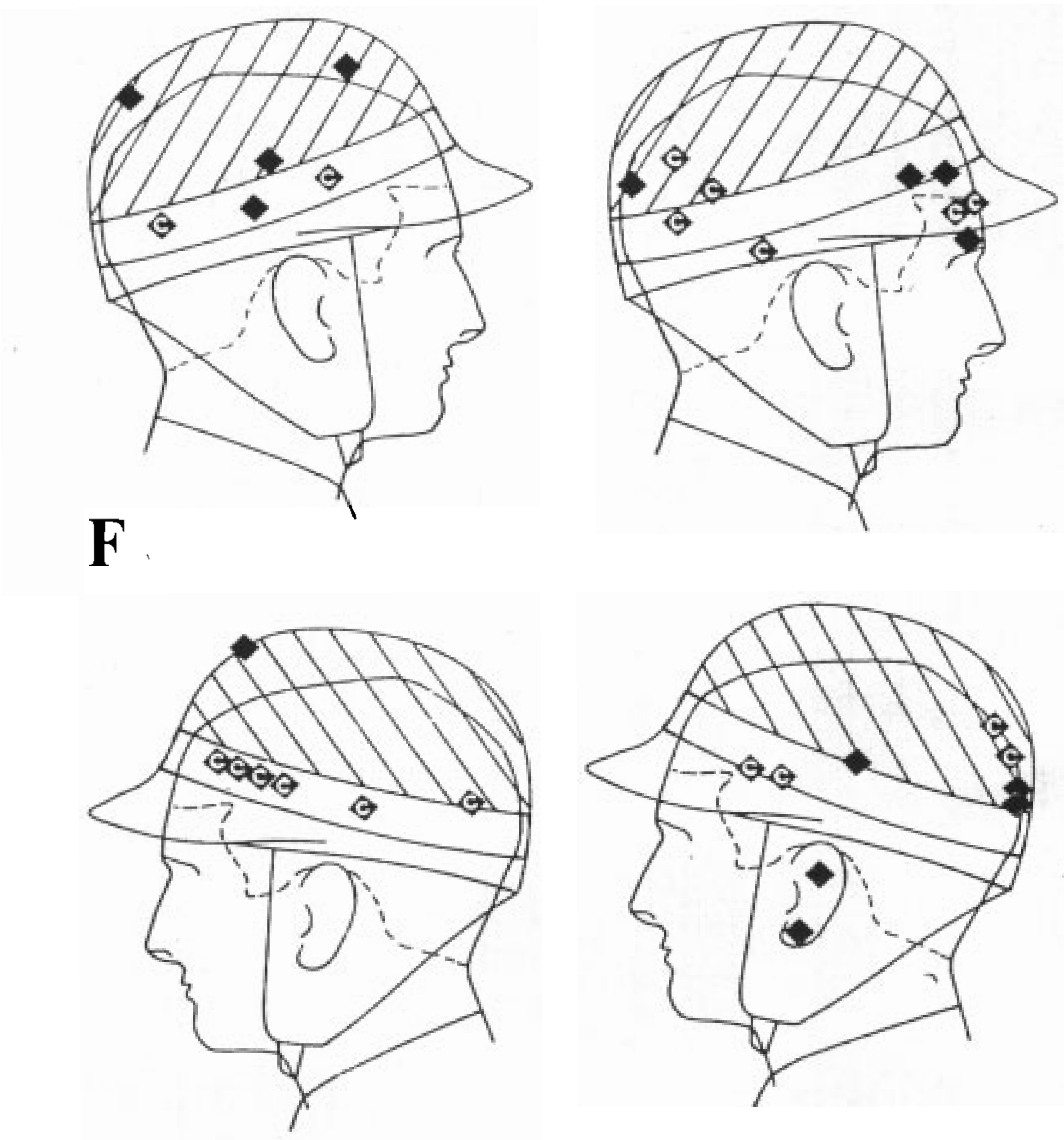
D


Distribution of Impact points (n=152) on the helmets (n=166)
front
impact right side without spec. inf. (n=7)
right side view
impact left side without spec. inf. (n=6)
left side view
impact without spec. inf. (n=33)
impact undefined (n=29)
top view

E



F



Cases where a helmet was worn, showing the position of impacts in relation to the shell of the helmet and the protective padding. The cross-hatched area indicates the extent of the padding. 'C' indicates an impact causing concussion.

Cases where helmets were not worn, showing the position of the impacts in relation to the area covered by the shell of the helmet and its protective padding. The cross-hatched area indicates the extent of the protective padding. 'C' indicates an impact causing concussion.