PERGAMON

Accident Analysis and Prevention 35 (2003) 287–292

ACCIDENT ANALYSIS & PREVENTION

www.elsevier.com/locate/aap

The efficacy of bicycle helmets against brain injury

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Received 14 May 2001; received in revised form 3 January 2002; accepted 8 January 2002

Abstract

An examination is made of a meta-analysis by Attewell, Glase and McFadden which concludes that bicycle helmets prevent serious injury, to the brain in particular, and that there is mounting scientific evidence of this. The Australian Transport Safety Bureau (ATSB) initiated and directed the meta-analysis of 16 observational studies dated 1987–1998. This examination concentrates on injury to the brain and shows that the meta-analysis and its included studies take no account of scientific knowledge of its mechanisms. Consequently, the choice of studies for the meta-analysis and the collection, treatment and interpretation of their data lack the guidance needed to distinguish injuries caused through fracture of the skull and by angular acceleration. It is shown that the design of helmets reflects a discredited theory of brain injury. The conclusions are that the meta-analysis does not provide scientific evidence that such helmets reduce serious injury to the brain, and the Australian policy of compulsory wearing lacks a basis of verified efficacy against brain injury.

Keywords: Bicycle helmet; Efficacy; Scientific evidence

1. Introduction

The meta-analysis of Attewell et al. (2001) is of 16 studies, mainly case-control and dated 1987–1998, of the efficacy of bicycle helmets against serious injury. The Australian Transport Safety Bureau (ATSB)[1] initiated and directed it and the minister in charge released a version of it as an ATSB report (Attewell et al., 2000). The minister is also responsible for the policy by which the federal Australian Government induced the states and territories to pass, in the early 1990s, the world's first legislation for compulsory wearing of helmets that comply with a mandatory standard set by federal legislation and revised in 1999.

The meta-analysis claims to provide scientific evidence of efficacy of helmets against injury to the brain. This claim and the worth of the meta-analysis as a support for compulsory wearing are examined here.

Eleven studies included in the meta-analysis report data on brain injury as such or symptoms attributable to it. They are Dorsch et al. (1987), Wasserman et al. (1988), Thompson et al. (1989), Wasserman and Buccini (1990), Spaite et al. (1991), Maimaris et al. (1994), Thomas et al. (1994), Thompson et al. (1996), Linn et al. (1998), Shafi et al. (1998) and Jacobson et al. (1998). All contain data for individual cyclists and their use of helmets. Except for some of the earliest, all helmets contained plastic foam to reduce the linear acceleration generated by impact, but the hard-shell helmets that predominated in the 1980s later gave way to no shell (soft) or thin (micro) shell designs, with more holes for ventilation.

2. Mechanisms of brain injury

2.1. Focal injury

In the early days of helmets for road users, all deaths from head injury and severe effects such as coma were attributed to lesions to the brain that are obvious at examination after death (Strich, 1961). These include so-called focal injuries (Gennarelli, 1993) which comprise contusions, lacerations and the subdural haematoma (SDH) that may follow. They occur at the site of impact when an external object which penetrates the skull or bone of a damaged skull strikes the brain. Cairns and Holbourn (1943) hypothesised that a hard-shell helmet could spread the force of a blow over a wider area and reduce such injury. They concluded from a study of accidents to motorcyclists that this was so.

Turning to the meta-analysis, nearly all helmets worn by cyclists in the study by Thompson et al. (1989) had hard shells. Efficacy to reduce fracture of the skull and

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[1] References to ATSB before 1999 are to the former Federal Office of Road Safety.

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PII: S0001-4575(02)00012-X

consequent focal injury to the brain might have been tested if the requisite data had been collected, but the study shows no thought of this; skull fractures and lesions to the brain are not recorded separately from symptoms of concussion. Linn et al. (1998), Maimaris et al. (1994), Wasserman and Buccini (1990), Spaite et al. (1991), and Shafi et al. (1998) report that cyclists not wearing helmets suffered many more fractures of the skull than wearers. The last two also report more lesions to the brain, but none of these five studies show any knowledge of mechanisms of brain injury, specify how many helmets had hard shells or relate brain lesions to skull fractures.

2.2. Closed head injury

Injuries to the brain, including contusion, haematoma and concussion, commonly occur without damage to the skull, lesions often being reported both at the site of impact and opposite it (Richardson, 1990). To explain this, Morgagni (1766) proposed a theory of coup and contre-coup. By the 1940s, it was expressed in terms of linear acceleration: the skull accelerates rapidly in line with a blow to the head and strikes the loosely attached brain near that site: coup injury. Then the brain moves away to strike the skull at the opposite side: contre-coup. Concussion was commonly attributed to haemorrhage until Denny-Brown and Russell (1941) identified its cause as physical stress on neurones, which they attributed to linear acceleration. Later investigators proposed a mathematical relationship between it and concussion, expressed as a head injury criterion (HIC).

To protect the brain, helmets were developed to absorb some of the energy of impact and reduce the rate of deceleration to a maximum HIC number, but this has been strongly criticised by Goldsmith and Ommaya (1983) and by Newman (1975) who concluded that the HIC is an unreliable and inconsistent measure of a helmet's effect on injury. This is not surprising, as it neglects the dominant cause of brain injury, angular acceleration.

2.3. Angular (rotational) acceleration

Holbourn (1943) proposed a theory of brain injury that has no role for linear acceleration as a direct cause and rejects the mechanism of coup/contre-coup. He started from the physical properties of the brain of being about as dense and incompressible as water and having low rigidity. Using models of the brain and skull, he deduced that linear acceleration arising from a blow produces only small shear strains which have no injurious effect on the brain. Forces of rotation, by contrast, produce large shear strains and cause the brain to slide along the internal surface of the skull. Blood vessels may then be ruptured, causing SDH. He attributed so-called contre-coup injuries to rotation.

Experimental evidence in support of Holbourn has since accumulated (Adams et al., 1982). Pudenz and Shelden (1946) observed, using high speed cinematography on monkeys with part of their cranium replaced with transparent material, that the brain rotated within the skull during impact and did not draw away from it. From the 1960s, the heads of primates were subjected to controlled acceleration, both linear and angular. Ommaya et al. (1971) reported that such experimental work supported Holbourn's view that only skull damage and rotation of the head are important and that pure (linear) head translation had never been demonstrated as an injury producing factor for the brain. They dismissed a variation of the linear acceleration theory by Gross (1958), which proposed that a blow to the head generates pressure waves, causing cavities to form at the opposite side of the brain and injure it as they suddenly collapse.

Ommaya and Gennarelli (1974) used apparatus that produced either pure translation or rotation of monkeys' heads through 45° without any impact and its possible confounding effects. They found that rotation resulted in paralytic coma or traumatic unconsciousness, but translation did not.

2.4. Diffuse injury

According to Henderson (1995), three out of four cases of brain injury sustained by road accident victims fall into the diffuse type, the commonest and mildest form being concussion. The severe form, now designated diffuse axonal injury (DAI), was first defined by Strich (1956, 1961). Her microscopic examination of brain tissue of patients who suffered extreme dementia until death found few lesions visible to the naked eye, but widespread diffuse degeneration of the white matter. She attributed it to shear strains resulting from angular acceleration.

Graham et al. (1995) noted that DAI is the commonest cause of disability after head injury, including the vegetative state, and that it occurs mainly in road traffic accidents. In Glasgow, 45 out of 177 patients with fatal non-missile head injury were found to have DAI, judged to be identical to that produced in the subhuman primate by angular acceleration (Adams et al., 1982). In Australia, 29 out of 62 patients fatally injured in traffic accidents had DAI of similar character (Blumbergs et al., 1989) and the brain of a child pedestrian who died after being struck by a car showed injuries associated with angular acceleration (McCaul et al., 1988).

The duration of angular acceleration is also a factor, as experiments with primates have shown. Over a short time at a high rate it mainly affects blood vessels, leading to SDH and contusions. A lower rate and longer duration produce DAI and traumatic coma (Adams et al., 1986).

3. Some implications for helmets

The testing and design of standard helmets continue to reflect the discredited theory that linear acceleration is the dominant cause of brain injury and to neglect rotation. Ommaya et al. (1971) therefore called for revision of the standards, to include protection against its injurious effects, but to no avail.

Cairns and Holbourn (1943) argued that the hard-shell motorcycle helmets of the time could reduce rotation; having a lower coefficient of friction than the head, a helmet would slide over objects, spreading a blow over a longer time. The argument may not hold for bicycle helmets. In tests involving a forward velocity plus a drop height of 1.4 m, Corner et al. (1987) showed that even helmets with hard polymer shells did not slide on impact. They recommended that shells should be very stiff with a low impact sliding reaction. Instead, "to overcome an obstacle in introducing mandatory wearing", the Australian standard was amended to allow soft shells as being more acceptable to users (Department of Transport and Communications, letter of 24 June 1992). Tests of impacts on asphalt at 34 km/h have since shown that soft helmets grab the surface, rotating the head and producing high angular accelerations (Andersson et al., 1993). Ventilation holes might well aggravate this effect.

Cairns and Holbourn (1943) also argued that the buffering action of the slings and hatbands of their helmets would spread a blow over a longer time and tend to diminish rotation, but standard tests do not show whether the liner of a bicycle helmet does this. In any case, the effect on the brain is uncertain; Gennarelli (1984) and Gennarelli and Thibault (1982) suggested that the use of padding in cars and motorcycle helmets decreases SDH, but the risk of DAI may increase.

Rotation and serious injury to the brain can occur without the head being struck at all, as in falls on the buttocks and whiplash injury (Ommaya and Gennarelli, 1974). The weight of a helmet would increase this effect (Corner et al., 1987), more so in children, whose neck muscles are weak.

The relaxing of requirements for helmets to have hard shells and limited ventilation openings is likely to have reduced protection of the skull and increased focal injury to the brain. A field study by McIntosh et al. (1998) found that helmets with soft shells tended to disintegrate on impact. In Australia, the review of the mandatory standard by the Department of the Treasury (1999) abandoned its load distribution test, which had been intended to ensure some protection against fracture of the skull. This was to the advantage of the helmets trade but was against independent advice (e-mail, 11 May 1998, to Treasury from Dr. R. Somers).

4. The policy setting

The meta-analysis is not a disinterested academic treatise, but a product of an authority responsible for a policy that made wearing of helmets compulsory, following official campaigns to promote it. The campaigns publicised effects of severe brain damage and claimed that helmets save lives and serious injury, but inquiries have revealed that competent public authority did not verify this.

ATSB asserted the efficacy of helmets before all of the studies included in the meta-analysis. In 1984, it told a parliamentary inquiry which recommended compulsory wearing, that "the wearing of safety helmets by bicyclists is the principal means of reducing casualties", but it was unable to provide supporting evidence (ATSB, letter of 25 September 1997). Nor have authorities reviewed the policy against new knowledge. A report of the NHMRC on football injuries of the head and neck (National Health and Medical Research Council, 1994) cited Dorsch et al. (1987), Wasserman and Buccini (1990) and Thompson et al. (1989), but, unlike ATSB, did not credit them with providing evidence that bicycle helmets do more than reduce superficial injuries to the scalp and other soft tissues. The NHMRC went on to warn that the wearing of helmets may result in greater rotational forces and increased diffuse brain injury, but ATSB failed to consider the implications for its policy (ATSB, letter of 8 December 1999).

Evaluation of the efficacy of helmets should be by competent public body independent of policy aims, and be open to public scrutiny to ensure that all relevant knowledge is brought to bear. The meta-analysis was not done like this. Nor was the 1999 review of the Australian mandatory standard by the Treasury Department, which has no scientific expertise and did not seek advice from qualified public authority. Yet, on the basis of these the Government unequivocally assured the public of the efficacy of helmets against injury, to the brain in particular (Boswell, 2000) and that compulsory wearing laws are beneficial (Hockey, 1999 and Attewell et al., 2000).

5. Discussion

5.1. The meta-analysis

The meta-analysis claims to provide scientific evidence that helmets protect against brain injury, but it is too narrowly based for that. It takes no account of scientific research which has shown the importance of rotation as a factor in brain injury and deficiencies in the design and testing of helmets. Neither it nor its included studies even acknowledge the existence of DAI. Consequently, it does not seek data in sufficient detail, and it makes no attempt to deal with findings that suggest helmets of standard design may not reduce rotation, even those of Corner et al. (1987) for ATSB itself.

The meta-analysis and many of its included studies purport to measure by indirect means the efficacy of helmet wearing by whole populations of cyclists. Inaccuracies due to the means being indirect might have been avoided by direct measurement if compulsory wearing had been introduced with due care in Australia and authorities like ATSB had set up systems to monitor details of injuries, cyclists and wearing of helmets. They did not.

Robinson (1996) attempted direct measurement for New South Wales and Victoria, using official data for casualties and helmet wearing. She concluded that compulsory wearing discouraged cycling by children by 36%. As their injuries declined less than commensurately and head injuries no more, they became worse off. Scuffham and Langley (1997) and ATSB's counterpart in New Zealand attempted it for New Zealand (Povey et al., 1999), the former concluding that an increase in voluntary wearing pending compulsion did not cause a decline in the proportion of serious head injury, and the latter finding that compulsory helmet wearing reduced head injuries by nearly 30%. The meta-analysis excludes all three studies on the grounds that population studies provide the weakest form of epidemiological evidence, but inconsistently cites the finding of Povey et al. (1999) approvingly. According to Robinson (2001) however, it is likely to be an artefact caused by failure to fit time trends in the model. Further, ATSB itself did a population study (FORS, 1997). It attributes to compulsory helmet wearing a 33% reduction in casualties to cyclists compared to 23% for all road users, but it takes no account of the decline in cycling.

While the meta-analysis excludes some errors of population studies, it introduces others of its own. According to Shapiro (1994) and Egger et al. (1998), its basic method was developed for obtaining more precise assessments from randomised controlled trials. If applied to case-control studies, confounding and selection biases often distort the findings, even with possible adjustments for known confounding factors, and the method may produce "very precise but equally spurious results".

Choice of studies for meta-analysis is critical. Attewell et al. (2000) acknowledges a challenge not to include those too diverse with respect to design, outcome measure, population and quality. Some differences among studies might be too great, however; these include reliance on self-reporting, coincidence with campaigns or laws to increase use of helmets, and the decrease in the proportion of hard-shell helmets from the earlier to the later studies. The last is noted, but not recognised as a confounding factor for brain injury. Important articles published in the proceedings of international conferences are not considered.

5.2. The included studies

To provide scientific evidence that helmets reduce serious injury to the brain, knowledge of mechanisms that cause it should guide the collection, treatment and interpretation of data, facilitating identification of confounding factors, but the hypothesis which all included studies purport to test is simply that helmet wearing reduces injury. This does not recognise the two distinct mechanisms of injury to the brain, impact to it resulting from damage to the skull, and rotation. None of the studies data distinguish between them. Thus, if helmets prevent damage to the skull, problematic for those without hard shells, consequent focal injury to the brain would be reduced, but this result could well mask failure to reduce angular acceleration and the injuries it causes, so-called contre-coup and DAI. DAI is not mentioned in any of the studies, yet it is responsible for severe neurological disability and the vegetative state, fear of which is an important motive for wearing helmets.

Subjects of the included studies should accurately represent the whole populations of interest, ideally being a random sample, but only Wasserman et al. (1988) approximates to it. The disparity between the 23% rate of helmet wearing in the control groups of Thompson et al. (1989) and about 6% for children in the whole population (DiGuiseppi et al., 1989) underlines this concern. Another concern is the assumption that helmet wearing does not affect propensity to have an accident, contrary to the conclusion of Spaite et al. (1991), who suggested that Dorsch et al. (1987), Wasserman et al. (1988) and Thompson et al. (1989) had not proved that the "protection" associated with helmet use is a direct effect rather than a result of other factors.

5.3. Wider issues

The meta-analysis and its included studies throw up issues of wider concern. First is the gap between science and action. Standards for helmets have been set and wearing promoted primarily to reduce serious injury to the brain, but knowledge of its mechanisms and of DAI have not entered into these actions, the meta-analysis or its included studies. Australian legislation for standards and compulsory wearing needed such knowledge to verify efficacy, but the meta-analysis says it was simply "a logical progression" after motorcycle helmet legislation, glossing over the failure to meet this need. Further, warnings about dangers of rotation and diffuse injury were ignored (Corner et al., 1987 and National Health and Medical Research Council, 1994).

Second, the rationale of the meta-analysis apparently is to uphold the policy of compulsory wearing of helmets, but its attempt to scotch criticism of their efficacy (Attewell et al., 2000) is unwarranted against the facts that the policy lacks the underpinning of proper advice and has been maintained without due regard to new knowledge. Similarly, the suggestion that the medical community in the UK supports compulsory wearing is invalid; the British Medical Association rejected it in 1998.

6. Conclusions

It is concluded that: (a) the meta-analysis does not provide scientific evidence that bicycle helmets, not being tested for capacity to mitigate the main factors that cause serious injury to the brain, do reduce it; and (b) the Australian policy of compulsory wearing of helmets lacks a basis of verified efficacy against brain injury, suggesting a need for an independent and open review taking account of relevant scientific research.

Acknowledgements

I thank Jenny Hargreaves, Mr. James Arnold, Mr. Colin Clarke, Mr. James Grieve, the Document Supply Service of the Australian National University and the library of the Australian Department of Transport and Regional Services for their assistance.

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