In: Transportation Accident Analysis and Prevention
Editor: Anton De Smet, pp. 141-177
ISBN: 978-1-60456-288-0


*Chapter 6*

# Bicycle Helmets: A Scientific Evaluation

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## Abstract

Actions by medical bodies and governments to encourage or compel cyclists to wear helmets have greatly increased the use of them over the last 20 years, but still their basic efficacy and the effects on public safety and welfare remain under question. This chapter shows that this unsatisfactory state of affairs came about because authorities acted without due reference to scientific knowledge of brain injury and did not monitor adequately the effects of their actions.

Protecting the brain from injury that results in death or chronic disablement provides the main motivation for wearing helmets. Their design has been driven by the development of synthetic polystyrene foams which can reduce the linear acceleration resulting from direct impact to the head, but scientific research shows that angular acceleration from oblique impulse is a more important cause of brain injury. Helmets are not tested for capacity to reduce it and, as Australian research first showed, they may increase it.

Australia has been important in the growth of use of bicycle helmets in the world, it being the first country to act, in 1989, to make wearing compulsory. This action was taken at the instigation of surgeons who had been influential in introducing compulsory wearing of motorcycle helmets and seat belts in cars. Other countries followed this precedent, but it is a poor one because it had scant regard for the traditional rights of individuals to protect their own persons, the supporting evidence of efficacy of helmets was weak and the risk of serious casualty to cyclists was falling at the time.

The introduction of compulsory wearing in Australia provided a unique opportunity to measure its efficacy in practice – but the detailed and nationally uniform monitoring of cycling and casualties needed for this was not done. Such monitoring as was done showed sharp declines in cycling with less than commensurate falls in serious casualties including deaths by head injury. Benefits of the exercise of cycling for health were lost and the risk of accident increased, possibly due to less safety in numbers: motorists seeing fewer cyclists tend to show less concern for them. But authorities have obfuscated these effects.

A thorough investigation of the efficacy of helmets and effects of compulsory wearing is needed, preliminary to review of the policy, but authorities seem to be unwilling or unable to learn from experience and are resisting pressure to take such action. There would seem to be a lack of scientific understanding among road safety authorities and a need for governments to take action to strengthen their competence. There is also a lesson for other countries which have followed the Australian precedent.

## Introduction

Actions by medical bodies and governments to encourage or compel cyclists to wear helmets have greatly increased the use of them over the last 20 years, but still their basic efficacy and the effects on public safety and welfare remain under question. This chapter shows that this unsatisfactory state of affairs came about because authorities acted without due reference to scientific knowledge of brain injury and without adequate monitoring of their actions.

Early in the last century, racing cyclists commonly wore so-called hairnet style helmets, made from leather. These were mainly to protect the scalp from abrasions and contusions, but in mid-century attention turned to protecting the skull and brain from damage. This followed the development of hard-shell motorcycle helmets in World War 2 and, after the war, synthetic polystyrene foam that is capable of absorbing energy from an impact. Motorcycle helmets comprise a hard shell to protect the skull from fracture and the brain from consequent injury, together with a lining of polystyrene foam which is intended to protect the brain by reducing the force that an impact to the helmet transmits to it. Until the 1990s, this was the standard design of helmets for cyclists too.

Since the 1980s, many public authorities around the world have acted, with the support of medical bodies, to encourage cyclists to wear helmets for protection from head injury, and some have compelled it. Millions of cyclists have complied and most people in countries where wearing has been encouraged now regard a helmet as normal safety equipment. Despite this, the published literature shows continuing controversy about the basic efficacy of helmets and the effects on safety and welfare which increased wearing is having, especially where it is compulsory. As a contribution to resolving these issues in the interest of sound public policy on safety in cycling, this chapter examines motives for wearing helmets, scientific knowledge that bears on their efficacy, and official encouragement of their use, including legislation which makes it compulsory. For the last, the examination centres on Australia, the first country to introduce such legislation. The knowledge used to support the legislation and the effects of it are assessed.

Australia is a federation in which six sovereign states form a nation, known as the Commonwealth, of 20 million people. The states and their populations are New South Wales 6.7 million, Victoria 4.9 m., Queensland 3.8 m., Western Australia 2.0 m., South Australia 1.5 m. and Tasmania 0.5 m. Power to legislate for the wearing of helmets within their borders rests with their parliaments. The Parliament of the Commonwealth of Australia has delegated similar power to its two self-governing territories, the Australian Capital Territory (ACT) pop. 300 000, and Northern Territory (NT) pop. 200,000.

## Why Wear a Helmet?

With a strong growth in motor traffic and accidents in Australia in the 1950s and 1960s, public concern about the safety of cyclists, both motor and pedal, increased and the world's first legislation to compel motorcyclists to wear a helmet was passed in the State of Victoria in 1961. By 1973, such legislation was in force in all states and cyclists were beginning to use helmets. The Standards Association of Australia[1] published the first Australian standard for bicycle helmets in 1977 and a committee of the Australian Parliament began an inquiry into motorcycle and bicycle safety [1]. In evidence to the committee, representatives of the Royal Australasian College of Surgeons (RACS) put much emphasis on injury to the brain as a threat to life and a cause of permanent intellectual incapacity [2]. The RACS had been influential in bringing about compulsory wearing of helmets by motorcyclists and, in the early 1970s, seat belts in cars. Consequently, the parliamentary committee recommended that cyclists should be advised of the safety benefits of helmets and that the possibility of compulsory wearing should be kept under review.

Nearly all deaths and permanent disablement from head injury are attributable to damage to the brain. Through the 1980s, there was growing public concern about the risk of these dire consequences to cyclists, and a strengthening expectation that helmets were the remedy. This is reflected in the parliamentary committee's final report, in 1985 [3]. It refers to the dreadful consequences of death or permanent incapacity from head injury and describes helmets as a life saving measure for children. Similarly, a committee of the Parliament of Victoria supported mandatory use of helmets on the grounds of averting permanent incapacity due to brain damage and saving lives, its report noting strong public support for this measure [4]. From 1984 to the 1990s, the Victorian Government mounted publicity campaigns urging cyclists to use helmets. The publicity emphasised these dire consequences of brain injury, but it demonstrated a lack of understanding of its main mechanism of occurrence according to the relevant science. One advertisement, depicting the smashing of an egg [3], would have misled the public about this. Other governments in Australia mounted similar campaigns, including an official advertisement in New South Wales which depicted a bicycle helmet and the message "Strap it on your brain" [5]. "Bicycle helmets save lives" became a favourite mantra of politicians [6].

In the USA, the Federal Government issued leaflets in 1998 which promote the use of bicycle helmets [7]. One tells readers that most deaths from bicycle falls and collisions involve head injuries and this means that wearing a helmet can save your life. "And if you do not wear one you are risking your life." Another says that brain injury is the leading cause of death and disability among people under the age of 24 and 80% of deaths in bike crashes result from it. A highlighted statement is that research shows that helmet use while bicycling can reduce the chance of sustaining a brain injury by 88%.

Clearly, the main motive for cyclists wearing helmets and governments promoting it is to reduce serious injury to the brain. The critical question, then, is whether helmets do this.

## Brain Injuries

### Early Medical Research

The two main types of injury to the brain in road accidents are focal and diffuse [8]. Focal injuries comprise lacerations, contusions and the subdural haematoma (SDH) that may follow. They commonly occur at the site of impact when an external object which penetrates the skull or bone of a damaged skull strikes the brain. But the brain may suffer focal injury

[1] Now Standards Australia

without the skull being damaged. Such injury often occurs both near the point of impact to the head and elsewhere on the brain, especially, and for a long time believed to be always, at the opposite side of it. To explain these closed head injuries, Morgagni in 1766 proposed a theory that became known as coup and contre-coup [9]. According to it, when the head is struck the brain first moves towards the site of impact to strike the skull and produce coup injury. The brain then bounces back so that it strikes the skull on its opposite side, resulting in contre-coup injury.

Till well into the 20th century, deaths from head injury and severe chronic conditions were attributed to lesions to the brain that are obvious at post-mortem examination [10]. As early as the 16th century, however, other traumas of the head were observed to occur without damage to the skull and with no obvious lesions to the brain; these are now known to be due to diffuse injury to it. Typical of mild diffuse injury are initial unconsciousness, slow pulse and pallor, this syndrome being designated cerebral concussion in the 18th century. A modern definition refers to grades of disturbance in consciousness and its causes in terms of strains affecting the brain [11]. Sometimes concussion occurs without any visible lesions being found. Conversely, experiments with animals and clinical examination of humans have shown that extensive lacerations of the brain may occur without it. As well as concussion, which is of short duration, fatal injury and chronic conditions where brain function is more severely affected and not reversible have long been known to occur without obvious lesions; these include coma, paralysis and dementia.

Several theories of the causes of concussion and the more severe conditions have been proposed. Movement of the brain against the unyielding skull as a result of abrupt deceleration of the head was suggested from the start, a mechanism akin to the coup and contre-coup theory [12]. After findings in autopsy early in the 18th century that fatal head injury could occur without contusion or haemorrhage of the brain, controversy about the cause of concussion continued for two centuries, according to Denny-Brown and Russell [13]. Some investigators held that concussion is a minor degree of cerebral contusion and is always related to haemorrhagic lesions, such as small capillary or petechial haemorrhages, which, it was suggested, could easily be overlooked. Findings from some autopsies and experiments with animals appeared to support the notion that haemorrhage of some kind was the proximate cause of concussion, as opposed to contrary hypotheses which attributed it to direct damage to nerve cells. At the onset of World War 2, a widely held view was that such damage was due to compression of the brain as a result of a heavy blow.

Denny-Brown and Russell also noted important effects which could not be explained by any existing theory; these included tangential bullet wounds being the most effective in producing concussion, prolonged coma occurring without evidence of increased pressure and the prevalence of prolonged confusion, disorientation and disordered intellectual function. They considered that the root cause of concussion and other serious brain injuries was still a mystery: “Ever since the time of John Hunter (1786) there has been a suspicion that whatever is the nature of concussion, that something must have importance in more severe injuries.” To try to solve the mystery, they experimented with animals. A solution was of more than academic interest; the military at the time wanted to know how to protect its motorcyclists from head injury.

In the experiments, the animals were subjected to blows to the head, their force being measured as the rates of linear acceleration generated. (These may conveniently be expressed in units equivalent to the acceleration due to gravity, g.) One experiment indicated that the critical acceleration to produce concussion was 1500 g. Unlike the experiments by previous investigators, where the head had always been fixed, in some of these it was allowed to move. This resulted in the interesting finding that a blow to a fixed head caused no concussion, though greater distortion of the skull should have occurred, but the same blow repeated with the head allowed to move 2.5 cm resulted in death. The experimenters concluded that "pure" concussion is the direct result of linear acceleration on neurones, but did not indicate how, and they still gave credence to the view that concussion could be produced by compression. They therefore distinguished between "acceleration concussion" and "compression concussion", adding that the latter requires a much greater force to produce the same effect and the mechanism is different. They did not suggest what the mechanism of "compression concussion" might be, except to say that it must be of great complexity.

## Protection

From at least as early as the third millennium BC, helmets have been used to protect the head in warfare [14]. The early helmets were made of copper and bronze, but in the Middle Ages iron was used, together with soft padding. With the advent of high velocity rifles in the $19^{th}$ century, helmets were little used, but in World War 1, with the high incidence of head wounds from slower-moving missiles such as shrapnel, steel helmets, which protect the skull from being penetrated, became standard equipment. Having a webbing cradle that distributed the load over a wide area and by stretching reduced the impact force on the head, they would also have given the skull some protection against damage from blunt impacts. Similar helmets have since been in regular use in warfare, with steel replaced by lighter synthetic material. Also, in industries such as mining and construction and some sports, helmets are worn to protect the scalp from abrasion and the skull from damage by fast-moving objects of low mass, such as falling stones and balls.

Neurosurgeons have been prominent in bringing about increased use of helmets and much of the research mentioned above was directed to protecting against head injury. In Britain, World War 2 brought a new urgency to it. Deaths to motorcyclists rose sharply, mostly due to head injury. As the British Home Army was making much use of motorcyclists and was anxious to protect them, it engaged the eminent neurosurgeon and professor of surgery at Oxford, Sir Hugh Cairns, to investigate.

Cairns carried out an empirical study of eight accidents to motorcyclists, one who was not wearing a helmet and seven, all military personnel, who were [15]. The non-wearer was killed and the seven wearers survived, most of them suffering only mild injuries to the head despite considerable damage to four of the helmets. Though Cairns stated that the purpose of his study was to advocate that all motorcyclists should use helmets, his conclusion on this point was equivocal. With such a small number of cases and no controls for confounding factors, it could hardly have been otherwise. The main significance of the study is its references to a new factor in consideration of brain injury: the angular acceleration involved in rotation. Cairns obtained advice on it from a colleague at Oxford, AHS Holbourn, a physicist who had done research on the angular momentum of light. It would appear that Holbourn was the source of Cairns's notes about rotation and some of his equivocation. For instance, Cairns says that his Case V suffered post-concussional syndrome, but that helmets cannot be expected to prevent it. In appraising case VI, he suggests that a period of unconsciousness lasting several days resulted from severe head injury from violent rotation of the head, and in his discussion section he says that helmets have the theoretical disadvantages that they increase the diameter of the head and so leverage and the likelihood of broken neck and rotational acceleration within the cranium. Cairns and Holbourn carried out a joint study in 1943 of 106 examples of head injury [16]. It concludes only that the hard-shell motorcycle helmets of the time reduced local damage to the brain and covering skull at the site of impact, and tended to lower the incidence of prolonged amnesia, though the figures were "rather small".

The research of Cairns and Holbourn was undertaken at a time of crisis, not only due to the pressures of war, but also owing to the state of scientific understanding of brain injury. Thinking about its causes had long been concentrated on the obvious: direct impact and the resulting lesions. The accepted explanation of the occurrence of lesions to the brain where the skull was undamaged was the coup and contre-coup theory, which had originated before the rise of modern science. Investigators were under pressure from the military to devise a practical solution to the problem of causes of brain injury, but there were unanswered questions, loose ends and contradictions in the existing theories. It was akin to previous situations where revolutions in scientific understanding had occurred. Every high school student of chemistry knows the story of how Lavoisier reinterpreted findings of previous experiments, overturned the far-fetched phlogiston theory of combustion and set that science on a new and fruitful path. Similarly, Copernicus and Galileo reinterpreted observations of the firmament which people had made for millennia. Ever more complex adaptations of the old Ptolemaic system had been made to try to explain the movement of the planets according to the seemingly obvious fact that the sun, moon and stars all revolved in spheres centred on the earth, but the new heliocentric explanation swept all that complexity away.

## A New Theory of Brain Injury

From his work with Cairns, Holbourn [17, 18] went on to expound a new theory of brain injury in which angular acceleration (rotation) is the principal factor. He deduced it from fundamental principles of physics: "The assumption that there is a mechanics of head injuries implies that, when the head receives a blow, the behaviour of the skull and brain during and immediately after the blow is determined by the physical properties of skull and brain and by Newton's laws of motion." He listed the most important physical properties of the brain as:-

a). uniform density, about the same as water;
b).extreme incompressibility, also like water, resisting changes in size;
c).low rigidity, unlike the skull, offering little resistance to changes in shape.

He argued that the brain is injured by its constituent particles being pulled so far apart that they do not join up again properly when the blow is over. Because the brain is so incompressible but has so little rigidity, the amount of pulling apart of its constituent particles is proportional to the shear-strain: the type of deformation which occurs in a pack of cards when it is deformed from a neat rectangular pile into an oblique-angled pile. Hence, shear-strains are the cause of injury, whereas compression and rarefaction strains are not. He noted an experimental finding that peripheral nerves continued to conduct when subjected to a compression strain due to a pure hydrostatic pressure of 10,000 lb. per sq. in. (69 megapascals), vastly greater than anything which can arise in a head injury. If, however, the pressure varies in different directions, it must involve some shear, which, even if very small, may be sufficient to injure a nerve; examples given are the injuries to nerves produced by crushing with forceps or by stretching.

Even where the skull is not deformed at all by a blow, Holbourn argued that forces of linear and angular (rotational) acceleration would change the velocity of the head and generate strains in the brain. Of these, only shear-strains are important factors in causing injury, but those which linear acceleration produces are small compared to angular acceleration. Hence, without an appreciable rotation, or deformation of the skull, there will be no injury to the brain.

Holbourn dismissed the theory of contre-coup as being without physical foundation; the brain being so incompressible, no empty spaces can be formed anywhere as a result of a blow. Therefore, it can never move away from the interior surface of the skull, but can only slide along it. "The idea that the brain is loose inside the skull, and that when the head is struck it rattles about like a die in a box, thereby causing coup and contre-coup injuries, is erroneous. The so-called contre-coup injuries are really due to rotation."

Holbourn demonstrated his theory by experiments using a model comprising gelatin in the shape of a cross-section of brain, slightly adhering to the inner surface of a water-filled wax "skull". The model was subjected to sudden rotations, such as might be caused by blows to the skull, and the resulting shear-strains in the gelatin were detected by polarised light. Correspondence of the patterns of shear-strains with typical injuries was shown. He argued that for rotations about any axis in the median plane, the large-scale injuries on each side of the strain would be approximately mirror-images, but the minor details need not be; they might be, as it were, negatives on one side and positives on the other. Consequently, the large-scale injury produced by the rotation which occurs when the head is struck centrally on the occiput is approximately the same as that produced by the opposite rotation from a blow to the middle of the forehead. He noted with interest a remark which Courville made in 1942: "Essentially identical lesions of the sub-frontal and anterior temporal regions result from contact of either the frontal region or the occipital region of the moving head."

He also offered explanations of the circumstances in which particular head injuries are observed to occur. For instance, rifle bullets cause severe injuries to the sca1p, skull and brain, but often do not produce concussion. This is because bullets, owing to their small mass have a high kinetic energy but a low momentum; they and other light and fast-moving objects cannot produce much rotation of the head. But when the moving object is a person and hits say a road, the kinetic energy may be low, but the much higher mass means that the momentum is high. The plainly visible injury is likely to be small compared with the invisible damage due to rotation. "This is no doubt why it is often said that it makes a difference whether the head or the object causing the injury is in motion - a statement which, taken at its face value, is clearly absurd." The direction and location of a blow can also be critical; for example, the favourite knock-out blow in boxing, to the chin sideways and upwards, produces rapid rotation of the head, but the correct "heading" of a soccer ball has little effect.

Holbourn concluded in 1943 that head injury is primarily a problem in pure physics and rotations are of paramount importance. In 1945, he summed up the position as follows. "In the vast majority of accidents to human beings, only skull-bending, fracture and rotation are of any importance; but, with sufficient experimental ingenuity, it would obviously be possible to produce injuries by other mechanisms: some of the experimenters who report results due to the other mechanisms may have had this ingenuity; others may be misinterpreting their experiments." [18].

The new theory of Holbourn did not find universal acceptance, and thought among professionals about mechanisms of closed head injury split into two distinct streams: that of science and that of technology. The former accepted that the new theory provided a more credible explanation of brain injury than the old, but realised that it needed to be tested in experience, first by scientific experiments. The predominant preoccupation of persons comprising the latter stream of thought was the practical matter of protecting people from head injury. To those persons the old theory was attractive because means to reduce linear acceleration were available, but how to reduce rotation was a problem. Owing to other priorities in the post-war world, very little experimentation to test the competing theories took place for two decades or more; meanwhile, the development of helmets for motorcyclists and cyclists proceeded according to the old theory.

## Testing of Theories

Predictions of the old and new theories have been tested against experience in three ways. The first is by scientific experiments to test their adequacy to explain the mechanism or occurrence of the kinds of brain trauma that were already known, namely, injury to blood vessels (such as laceration, contusion and haemorrhage), and dysfunction (such as concussion, coma and dementia). As ethics limit the scope of experiments with human subjects, scientists have resorted to suitable approximations; these include use of animal and, more recently computer, models, cadavers, and, for head injuries of low severity, such as mild concussion, human volunteers. Most experiments with animals have been with primates. As they are our nearest relatives, the problem of scaling-up results of experiments on their brains to obtain knowledge valid for human beings is thereby minimised.

The second test of theories is to explain other trauma or phenomena which had not previously been observed or understood, including assessment of the explanations by experiment. The third test is usefulness in explaining clinical observations.

### Experiments: Known Trauma

Some experimental support for the new theory's mechanism of trauma to the brain came quickly, in the form of evidence from experiments with monkeys with part of their cranium replaced by transparent material so that any movement of the brain in response to an impact to the head could be recorded by high speed cinematography [19]. It was found, as Holbourn had predicted, that the brain rotated within the skull during impact and did not draw away from it.

From about 1960, experimental research was conducted, mainly at universities in the United States and at Glasgow, in which heads of primates were subjected to controlled acceleration, linear or angular. Such research published in the 1960s showed that angular acceleration exceeding 40000 rad/sec$^2$ without significant impact to the head (whiplash) could produce concussion in monkeys if its duration exceeded 10 msec. It was also found that whiplash without direct impact to the head could produce subarachnoid haemorrhage and cerebral contusions. Noting that it is easier to injure the much larger brain of man, the authors estimated that angular acceleration of 6-7000 rad/sec$^2$ may suffice. They also mentioned that cerebral concussion is a common result of whiplash injury in man [20]. An estimate made later is 1800 rad/s$^2$ for tolerance of angular acceleration against cerebral concussion [21].

In 1971, Ommaya et al. reported that experiments in which rhesus monkeys were struck on the head gave support in principle to Holbourn's view that only skull bending, fracture and rotation of the head are important factors in injury to the brain [22]. They suggested that, in the absence of skull fracture, brain was injured primarily when it was distorted by shear stresses, the most generalised of which were due to rotation. Blows to the front of the head usually produced coup lesions alone and those to the back of it usually resulted in both coup and contre-coup. They also considered a rival theory of the mechanism of injury to the brain. According to it, translation (linear acceleration) of the head would produce zones of negative pressure and cavitation in the brain. Ommaya et al. commented that data from human autopsies as well as from their experiments could not be explained by that theory, and concluded that the skull distortion and head rotation hypothesis explains a greater number of observations on coup and contre-coup injuries than either rotation alone or the translation/cavitation theory. "Indeed, pure head translation has never been demonstrated as an injury producing factor for the brain."

Research in the 1970s into focal and diffuse injuries in different parts of the brains of squirrel monkeys tested separately the effects of rotation and linear acceleration [23]. The experiments showed that linear acceleration of the head up to 1400 g. in the horizontal plane produced contusions and intracerebral haematomas, though not cerebral concussion. In further experiments, the heads of squirrel monkeys were subjected to rotation or translation. All animals in the rotated group experienced sudden onset of paralytic coma or traumatic unconsciousness. None of the translated group showed this effect, but merely developed a few focal lesions. At linear accelerations up to 1230 g, it was possible to produce cerebral concussion only when the head was allowed rotate. The authors suggested that pure translation does not produce any significant diffuse effects in the brain-stem or cortices, these being the sites of cerebral concussion severe enough to produce paralytic coma. According to Adams et al. in 1983, all of the major types of brain damage that occur in man as a result of a non-missile head injury have been reproduced in subhuman primates subjected to inertial, i.e. non-impact, controlled angular acceleration of the head. Thus, nothing needs to strike the head nor does it need to strike something to produce these various types of brain damage. What matters are the degree, direction and duration of the acceleration/deceleration impulses [24].

## Other Trauma and Phenomena

As noted above, chronic conditions have long been known to occur where functions of the brain are severely and irreversibly affected but no damage to it is apparent to the usual pathological examination or autopsy. Strich noted that little was known about the pathology of brain damage in such cases [10]. She suggested that this was because few of them had reached neuropathologists, who in any case had been content to attribute all deaths from head injury and severe effects such as coma to lesions that are obvious at examination after death, it being too tedious to examine a brain histologically. But she made such tedious examinations. With a microscope, she made detailed observations of the brains of twenty patients who had received apparently uncomplicated head injuries and yet had remained in a state of extreme dementia until they died. Almost all of them had been injured in road accidents, only two had fractures of the skull and there were no lacerations of their brains, significant intracranial haemorrhages or evidence of raised intracranial pressure. All patients were unconscious from the time of the accident and only one improved enough to leave hospital. Her microscope showed widespread diffuse degeneration of the white matter of their brains. This condition, which Strich was the first to define, is now called diffuse axonal injury (DAI). It represents a severe form of concussion. With reference to Holbourn, Strich attributed it to shear stresses and strains set up during rotational acceleration. She also found evidence of the asymmetric degeneration of nerve fibres, hemisphere v hemisphere, which Holbourn had predicted.

DAI similar to that suffered by human beings has been produced experimentally in monkeys, in conditions simulating a fall or an auto crash. Gennarelli et al. [25] produced traumatic coma in 45 monkeys by subjecting their heads to angular acceleration successively in three directions. The authors stated that their results demonstrated that angular acceleration of the head causes axonal injury in the brain proportional to the degree of coronal (lateral) motion. The type of axonal damage seen in the animals and its distribution in the brain closely resembled the situation encountered in severe brain injury in humans. They concluded that axonal damage caused by angular acceleration of the head in the coronal plane is a major cause of prolonged traumatic coma and its sequelae. With angular acceleration in other directions, the damage was much less.

The rate and duration of angular acceleration are also important. Over a short time at a high rate, angular acceleration mainly affects blood vessels, leading to contusions and subdural haematoma (SDH). A lower rate and longer duration produce DAI and traumatic coma. These effects have been shown in experiments where the heads of rhesus monkeys were rotated through a 60 degree arc over 5-25 msec. [26] At acceleration below $1.75 \times 10^5$ rad/sec$^2$, of duration less than 5 ms, acute SDH and concussion resulted. Beyond 5 msec, acute SDH did not occur but DAI did. When acceleration exceeded $1.75 \text{ X } 10^5$ rad/sec$^2$, acute SDH occurred at these longer durations also. As pulse duration increases, i.e., strain rate decreases, larger values of acceleration are required to cause failure of the bridging veins. This study demonstrates that acute SDH due to ruptured bridging veins occurs by the onset of rapid rates of angular acceleration of the head, i.e., high strain rate. Impact to the head is the most common cause of acute SDH, though no blow to it is necessary.

A well-known phenomenon which had defied explanation was that a woodpecker can strike its beak repeatedly against a tree with considerable force, yet with no sign of concussion or brain injury. May et al.[27] considered a suggestion that the jarring impact was absorbed by cartilage or muscle and did not reach the brain, but found it not satisfying; if much of the impact were absorbed, the beak would not be effective in boring holes! May et al. [28] recorded a drilling woodpecker by high-speed cinematography and examined the films both visually and by a micro-densitometer and computer-imaging technique. These showed that the woodpecker set about its work like a carpenter using a hammer; before winding back to strike, it often made one or two preliminary taps on the target, presumably to line it up. After that, its drilling trajectory was essentially linear, not, in what would seem more natural, the form of an arc, like swinging a hammer. To achieve such a trajectory requires a more complex neuromuscular system, which is *less efficient* in the mechanical sense of effort expended to drill. Its only advantage is that it results in very little, if any, rotation of the head – a remarkable endorsement from the world of nature of the importance of that factor in brain injury. The observed velocity at impact was 6-7 m/s and linear deceleration was about 1000g. Even taking account of the smaller size of the bird's brain compared to man, May et al. described withstanding repeated impact forces of such magnitude as a formidable achievement – but it is entirely consistent with the theory of Holbourn.

## Clinical Observations

According to Gennarelli and Thibault, acute SDH is the most important cause of death from head injury in general and it most commonly results from tearing of veins that bridge the subdural space [26]. In 1982, those investigators examined clinical data for 434 patients who were admitted to hospital for a non-missile head injury. Of the acute SDH group, the cause of injury was a motoring accident for 72 % and a fall or assault for 24%. By contrast, 89% of the DAI was due to motoring accident and only 10% to a fall, and it was observed only in individuals who had fallen from a considerable height. This observation is consistent with DAI being attributable to acceleration forces that are more severe and of longer duration than are likely to occur as the result of a simple fall from not more than a person's own height [29].

According to a study in Australia, 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 [30]. Other studies in Australia showed, respectively, that 29 out of 62 patients fatally injured in traffic accidents had DAI of similar character [31] and that the brain of a child pedestrian who died after being struck by a car showed injuries associated with angular acceleration [32]. 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 [33].

As for disability after head injury, including the vegetative state, Graham et al. noted in 1995 that DAI is the commonest cause and that it occurs mainly in road traffic accidents [34].

## Summary of Research

According to Adams et al., experiments based on controlled angular acceleration of the head in non-human primates and carried out in the 1970s and 1980s at the Universities of Pennsylvania and Glasgow have shed considerable light on the pathogenesis of brain damage brought about by non-missile head injury in man [35]. There are two fundamentally different types of brain injury resulting from acceleration forces: injury to blood vessels and injury to axons. Angular acceleration over a very short time through $60^0$ in the sagittal plane has its principal effect on blood vessels (including the bridging veins) leading to acute SDH; and slower acceleration, particularly in the lateral plane, produces DAI.

The experiments gave special attention to direct comparison of the contributions of linear and angular acceleration because the widely accepted Head Injury Criterion for head injury is based on measurements of the former – see below. The essential role of angular acceleration in producing cerebral concussion was shown, the threshold being estimated as 2000-3000 rad/sec$^2$. Translation was also responsible for brain injuries, albeit only focal, and did not produce concussion. “Thus, in considering protection of the brain both the amplitude of head rotational motion must be reduced and contact phenomena must be mitigated. Hitherto, the latter has been considered of prime significance and insufficient attention has been given to rotation.” Lesions and acute SDH were produced by contact pulses of less than 5 ms duration; these correspond to impacts upon a rigid plate. By contrast, conditions resulting in DAI were found to be rotation, distributed loading and soft impact lasting more than 10 ms. Interestingly, padded impacts fall into the soft category, their duration being stated as 12-18 ms.

As Gennarelli put it, SDH and DAI share a common mechanical cause, which differs only in degree [36]. SDH is due to vascular injury that is caused by relatively short duration angular acceleration at high rates. These are the circumstances that occur in falls where the head rapidly decelerates because of impact to firm, unyielding surfaces. DAI is also due to angular acceleration of the head, but occurs most readily when the head moves coronally and it only occurs when the acceleration lasts longer and its rate is lower than is needed to produce SDH.

Along with the support which research has provided for the new theory, it has discredited the notions of coup and contre-coup and of linear acceleration of the brain being a major factor in injury to it. Basic to the former notion is that contre-coup contusions should always occur on the side of the brain opposite to the site of impact. To early observers, this appeared to be so, but closer examination has shown that it is not. Rather, the so-called contre-coup injuries mainly occur in the frontal and temporal lobes and in the sylvian fissure, independent of the site of impact [22, 33, 37]. As regards correlation of linear acceleration and degree of cerebral concussion produced, Gurdjian et al. subjected dogs to hammer blows to the head [38]. The results ranged from severe concussion at linear acceleration of less than 100g to none at more than 700g. The authors concluded that no correlation was shown.

# Helmets

"To every complex problem there is a solution which is simple, neat and wrong." - HL Mencken

## Protecting Cyclists

The practical matter of protection has dominated the stream of thought that linear acceleration is the main factor in brain injury. Adherents to that stream knew that linear acceleration could be reduced by padding in a helmet, but to accept the new theory would mean finding effective means to reduce rotation of the head in an accident, a challenge which was and is problematic. In any case, in the immediate post-war period the new theory was untested and DAI, the direst consequence of angular acceleration, had not been defined.

Cairns and Holbourn) argued in 1943 that the hard-shell motorcycle helmets used then 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 [16]. Later research on standards for bicycle helmets suggests, however, that the argument does not hold for those lacking hard shells – see below.

Protecting motorcyclists and then cyclists from brain injury became important to the public, the medical profession and legislators from about 1960 onwards. The task of finding means to do it should have started from scientific knowledge of types and causes of brain injury. Then it would have been clear that the critical requirement is to reduce angular acceleration of the brain from an oblique impulse. The impulse might not even require an impact; 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 [23]. Instead, the thinking about means of protection started from what seemed to be the simple solution: wearing helmets, like soldiers and miners. The design of helmets intended to protect motorcyclists and cyclists from brain injury then proceeded according to the old theory, hastened by the development of an international industry mass-producing polystyrene foam liners capable of absorbing energy associated with linear acceleration from a direct impact. The early helmets comprised a hard shell which could protect the skull from damage and a polystyrene foam liner which could mitigate the transmission of linear acceleration to the head. It seemed that these "new generation" helmets were superior to the older types and would protect the brain, but the standard tests of them did not include capacity to reduce angular acceleration. Therefore, the only certain protection for the brain was against focal injury consequent upon damage to the skull.

Following the old theory that linear acceleration is the cause of concussion, much research effort has been devoted to attempts to estimate the threshold at which it occurs. In the 1960s, a cerebral concussion tolerance curve was developed at Wayne State University in the USA, to show the variation of the tolerable effective linear acceleration of the head as a function of the duration of impact load. From this, a severity index and Head Injury Criterion (HIC) were developed mathematically and have been used by safety authorities. Not surprisingly, none of these criteria has proved to be satisfactory for evaluating protective headgear [39], but it has suited elements of the medical profession, governments and those in the business of protection to make use of them, and implicitly attribute brain injury to linear acceleration.

If the task of finding how to protect against brain injury had started with the relevant science, other means than wearing helmets might have been given serious consideration. As long ago as 1971, Ommaya et al. pointed out that the design of motorcycle helmets and related safety devices was based on the head injury tolerance curve that relates brain injury to linear acceleration, but reducing rotation should be the aim for protection [22]. Their point was supported by experiments in which the heads of 12 monkeys were subjected to occipital impacts comprising both linear and rotational components [40]. Six of the monkeys wore cervical collars, which would reduce flexing of the neck and limit the rotation of the head to approximately that of the body. None of them suffered concussion, but all six not wearing collars did. This was so even though the translational (linear) motions of the heads of the monkeys wearing collars were higher than the non-wearers. Ommaya et al. commented that a cervical collar, which limits rotation but does not reduce linear translation of the head, efficiently raises the threshold for cerebral concussion after occipital impact. Noting that helmets were designed on relating brain injury to linear head acceleration, disregarding the effect of rotation, they called for urgent revision of the standards for them. “Until this revision is achieved we may continue to expect high mortality and morbidity among wearers.”

In their study of woodpeckers, May et al. considered the implications of their findings for helmets to protect human heads [28]. They did not credit helmets (with hard shells) to have capacity to do more than to distribute the force of an impact and resist penetration and abrasion. Consequently, they suggested discarding the “magical notion” that wearing a helmet is sufficient to protect against brain damage; rather, it is necessary to develop systems that will dampen sudden rotary movements that could create shearing strains in brain tissue. In that respect, evolution is well ahead of the human technology of the system now in use, that is, helmets. May et al. also suggested that, in anticipation of imminent injury, persons at risk should tighten their neck muscles in a chin-down position, which has been shown to decrease peak angular velocity and angular acceleration [27]. In this way, professional boxers, who of course have strong neck muscles, can absorb much head battering if they are prepared and see it coming

For automotive injuries, Gennarelli and Thibault commented that the lower acceleration rates and longer pulse durations which result from use of energy-absorbing devices decrease the conditions that lead to acute SDH, but might place the patient in jeopardy of developing DAI which, in its severe form, is just as bad [26]. “Thus it is possible for use of well-meaning protective devices to allow one bad injury instead of another.” Motorcycle helmets were mentioned.

In Australia, an inventor who was concerned to protect motorcyclists from paraplegic injuries suffered as a result of “whiplashing” of the head testified in 1977 to the committee which was inquiring into motorcycle and bicycle safety [41]. He demonstrated a prototype of a device comprising a long piece of metal covering the top of the head and going down the back which, it would appear, would similarly limit the rotation of the head to approximately that of the body.

## Promotion of Use

Governments in several countries have actively promoted the use of bicycle helmets. Some, including Australia, New Zealand, Spain and Israel have gone on to make wearing compulsory, as have some jurisdictions in the USA and Canada. As is the case in Australia, it would seem that these actions were taken without first verifying the efficacy of helmets against brain injury. As noted above, the US Department of Transportation has published leaflets advocating the merits of helmets. In them are highlighted statements to the effect that helmets can reduce the risk of head injury by 85 % and risk of brain injury by 88 %; one leaflet states that these are facts. The numbers are the same as those stated in the conclusions of a study by Thompson et al.[42] and have been strongly criticised in the scientific literature, but the response to an inquiry to the Department showed that it had not done any independent study to confirm them [43].

The Department for Transport in the United Kingdom has a more cautious attitude. While believing that it is sensible for cyclists, especially children, to protect themselves by wearing a helmet, the Department concedes it to be an open question, as at April 2007, whether this may increase the risk of brain injuries from rotational motion in impacts to the head [44].

While several provinces in Canada have legislated for compulsion to wear a helmet, Transport Canada, a federal government agency, has made it clear that it does not support such action. That agency made an examination of data covering the period 1975 – 2002. It concludes that Canada is replicating the experiences of Australia and the US, where no effect of increased helmet use among cyclists can be detected from prevailing fatality trends [45]. Transport Canada has therefore suggested that traffic authorities should put their efforts into other proven measures, including pressure on aggressive drivers to change their habits, educational efforts to improve cyclists' skills and better lighting of bicycles at night.

## Standards

In many countries, standards of performance are set for helmets used in cycling and motorcycling. The most important requirement of the standards is that the force of a direct blow to the helmet in specified testing conditions should be reduced so that the linear acceleration of a head form within it does not exceed a stated maximum. Since it is much more difficult to make the equivalent measurements of angular acceleration and no practicable means of reducing it has been developed, it does not enter into standard tests [46, 47]. Bicycle helmets are not designed to reduce angular acceleration. Driven more by helmet suppliers' technology than scientific knowledge, the standards therefore neglect the major cause of brain injury, rotation of the head as a result of oblique impact. Such standards have been criticised for more than thirty years. As noted above, research scientists have called for urgent revision of them, but the call has been to no avail; authorities have not been willing to deal with the complexities involved.

The second report of the Australian House of Representatives committee in 1985 recommended legislation to compel the wearing of bicycle helmets [16]. The committee recognised that in support of it a mandatory standard was needed to assure the public of the efficacy of helmets. With the aim of making helmets more acceptable to the public, the committee recommended research on whether they could be better ventilated and lighter, such as by dispensing with hard shells. But the research, by Corner et al [48], did not simply endorse such revisions. Corner et al. reported that the standard tests were deficient in merely protecting the brain against a direct blow but not in reducing angular acceleration. To minimise it, they said that helmets should have very stiff shells with a low impact sliding reaction. In experiments simulating crashes with helmeted dummies falling forward over the handlebars at 45 km/h, they found angular acceleration averaging 58,000 rad/s$^2$, about 30% higher than the polymer full-face motorcycle helmets tested. This angular acceleration compares with 4500 rad/s$^2$ for the onset of vein rupture and 1800 rad/s$^2$ for cerebral concussion [21]. The authors also noted that tests involving a forward velocity 8.3 m/s, or 30 km/h, plus a drop height of 1.4 metres had shown that even helmets with hard polymer shells did not slide on impact, presumably due to the high vertical force acting. In those tests, peak angular accelerations of 4800-15400 rad/s$^2$, varying greatly by kind of surface, were reached after 5-10 ms, falling to a fourth of those values or less by 10-13 ms. Corner et al. commented that the standard tests for helmets do not reflect the actual crash situation which usually involves considerable horizontal acceleration of the head as well as vertical acceleration. These result in high angular acceleration of the head on impact.

Despite the recommendations of Corner et al., the mandatory standard has allowed soft-shell helmets from 1990 onwards, these being considered more acceptable to users. Helmets with soft shells or no shells have become the norm. In 1996, a leading Australian manufacturer said, "The helmet industry has certainly changed over the past 16 years and bicycle helmets are now a consumer product. Heavy, bulky style hard helmets have virtually been replaced by the lightweight aerodynamic micro shell styles that we see today. In fact the bicycle helmet industry has become almost a fashion industry and this is all related to consumer demand. The original Rosebank Stackhat outer shell thickness is 3 mm whereas the products manufactured today are approx. 0.7 mm thick."[49]

Later research supports the findings of Corner et al. on the effects of helmets on rotation. In 1991, Hodgson reported tests of hard shell, micro-shell and no-shell helmets in skid-type impacts on concrete inclined at angles from $30^0$ to $60^0$, from a speed around 12 km/h [50]. The hard and micro-shell helmets tended to slide, but the concrete surface penetrated and hung onto the nylon cover and liner of the no-shell helmets, forcing the neck into flexion. In a study of impacts of helmets on asphalt at 34km/h, Andersson et al. showed that, unlike hard-shell helmets which slide, soft helmets grab the surface, rotating the head and producing angular accelerations of four to six times the tolerable maximum [51]. Ventilation holes might well aggravate this effect. The relaxing of requirements for helmets to have hard shells and limited ventilation openings is also likely to have reduced protection of the skull and increased the risk of focal injury to the brain. A field study of accidents to 42 helmeted cyclists in Australia found that "soft-shell helmets tended to disintegrate on impact, and although only a single impact occurred, a helmet should remain intact to provide protection during second impacts" [52].

Cairns and Holbourn argued in 1943 that the buffering action of the slings and hatbands of the helmets they studied would tend to diminish rotation [16], but standard tests do not show whether the liner of a bicycle helmet does this. To the contrary, Corner et al showed in experiments involving impacts to the jaws of cadavers that the added mass of a helmet has the effect of increasing the rotation which a glancing blow may impart to the head upon impact. Later experimental research made similar findings. In the USA, King et al., measured angular acceleration generated in impacts to dummy heads which were either bare or wearing a bike helmet lined with expanded polystyrene foam [53]. In five of nine tests, angular acceleration was reduced when a helmet was worn and in four it was increased. In the UK in 2007, St Clair and Chinn made tests of oblique impacts at an angle of incidence of $15^0$ and horizontal speed of 8.5 m/s [44]. Quoting the published abstract of the research (at http://www.trl.co.uk/store/report_detail.asp?srid=6190&pid=220):

"Concern has been expressed that current bicycle helmets may increase the risk of brain injuries from rotational motion. A range of child and youth bicycle helmets have therefore been tested to evaluate their linear and oblique impact performance. This data was used to assess the propensity of the helmet to influence rotational motion and was considered against post-mortem human surrogate data to allow comparison of the risk of injury to that of an un-helmeted head. Unhelmeted post-mortem human surrogate data indicates that a simple skull fracture for an unhelmeted head (injury rated as AIS 2) may occur at 5kN - 6kN which corresponds to between 100g and 150g for a head mass of between 4kg and 5kg. Assuming that the response of the unhelmeted head is similar to the helmeted head during an oblique impact at 8.5m/s at 15º, this may generate between 7500rad/s² and 12000 rad/s² of rotational acceleration. This is potentially more severe than the 3000rad/s² to 8500rad/s² measured during abrasive and projection oblique tests with size 54cm (E) helmeted head-forms. However, for the most severe cases using a size 57cm (J) headform, rotational acceleration was typically greater than 10,000rad/s$^2$ and increased to levels of 20,000rad/s$^2$, a level at which a 35% - 50% risk of serious AIS3+ injuries is anticipated. Overall, it was concluded that for the majority of cases considered, the helmet can provide life saving protection during typical linear impacts and, in addition, the typical level of rotational acceleration observed using a helmeted headform would generally be no more injurious than expected for a bare human head. However, in both low speed linear impacts and the most severe oblique cases, linear and rotational accelerations may increase to levels corresponding to injury severities as high as AIS 2 or 3, at which a marginal increase (up to 1 AIS interval) in injury outcome may be expected for a helmeted head. The true response of the bare human head to oblique, glancing blows is not known and these observations could not be concluded with certainty, but may be indicative of possible trends. A greater understanding is therefore needed to allow an accurate assessment of injury tolerance in oblique impacts. Linear impact performance, head inertia and helmet fit were identified as important contributory factors to the level of induced rotational motion and injury potential. The design of helmets to include a broad range of sizes was also concluded to be detrimental to helmet safety, in terms of both reduced linear and rotational impact performance. The introduction into EN1078 of an oblique impact test could ensure that helmets do not provide an excessive risk of rotational head injury."

The data on angular acceleration that were obtained are of limited value. St Clair and Chinn equated the impact in their tests to a vertical fall of only 25 cm when travelling at 30 km/h. Clearly, many vertical falls in cycling accidents could be more like a metre, so that the angle of incidence would greatly exceed $15^0$. In collision with a moving motor vehicle, when the most serious injuries to cyclists occur, the speed at impact might well be much greater than 30km/h. Further, the results using a size 57 cm headform are described as the most severe cases, but that size is only typical of a youth or small adult. Many adults would wear larger helmets. All of these factors would work to increase the generation of angular acceleration. In real life, then, wearing a helmet might aggravate consequent injury to the brain much more than these tests indicate.

Similarly, in Australia the National Health and Medical Research Council (NHMRC) noted in its report on football injuries of the head and neck that helmets may possibly reduce the incidence of scalp lacerations and other soft tissue injury, but :

"The use of helmets increases the size and mass of the head. This may result in an increase in brain injury by a number of mechanisms. Blows that would have been glancing become more solid and thus transmit increased rotational force to the brain" [54].

Corner et al. considered that reducing angular acceleration was an unsolved problem, but attempts have been made to find a solution. In 2003, Phillips devised a prototype motorcycle helmet to reduce angular acceleration, but the prospects for commercial production of an equivalent for cyclists would appear to be poor [55].

An effect of a helmet spreading a blow over a longer time is also a consideration. Cairns and Holbourn argued that the slings and hatbands of the helmets they studied would do this [16], but in any case the effect on the brain is uncertain; a lower rate and longer duration of angular acceleration may result in more DAI and traumatic coma.

It is clear from the investigations described above that there can be no confidence that wearing a bicycle helmet of current design can ensure protection against either cause of serious injury to the brain. If helmets do not have hard shells, their capacity to protect the skull from damage and the brain from consequent focal injury is in doubt. Standard tests do not include capacity to reduce angular acceleration. Worse, in some circumstances wearing a helmet can increase the angular acceleration which an oblique impulse imparts to the head, increasing the risk of damage to the brain, especially diffuse axonal injury. The Australian experience of the compulsory wearing of helmets, discussed below, provides probably the best available measure of their value in practice.

## Australian Legislation

From 1985 to 1989, the political attractiveness of legislating to compel cyclists to use helmets increased. Seat belts in cars and motorcycle helmets were precedents and the RACS was urging the "third major step"[56]. In response, the Prime Minister of Australia announced on 5 December 1989 an invitation to the states and self-governing territories to legislate for compulsory wearing of bicycle helmets, among a range of other measures. As an inducement, he offered additional funds for roads. The Prime Minister categorised compulsory wearing of bicycle helmets as a known and effective measure, though it had never been tried anywhere in the world then. Presumably, this statement reflected the notion that compulsory wearing of bicycle helmets was a progression from motorcyclists [57]. Yet there are a host of differences between the two [58] and the many deficiencies which Corner et al. found in the standard have never been refuted. Also, the evidence of the efficacy of helmets upon which parliamentary committees had recommended compulsory wearing was weak – see comment below.

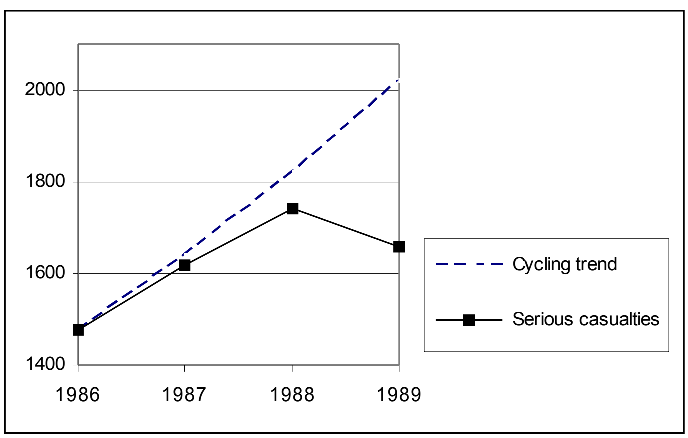


Figure 1. Cycling and serious casualties (fatal & hospitalised), Australia.

Nevertheless, compulsory wearing became law nationwide, beginning with Victoria in 1990 and ending with the ACT in 1992. The official rationale for it is to minimise the medical and other public costs of accidents to cyclists. Ironically, at the time of the Prime Minister's announcement, the risk of serious casualty to cyclists had actually been falling; Figure 1 (reproduced from Curnow [70] with kind permission of *Health Promotion Journal of Australia*) shows serious casualties well short of the strong growth trend in cycling.

Several other countries have followed Australia's lead, but it is a poor precedent, due to the falling risk of serious casualty, to the weak supporting evidence of efficacy of helmets, giving no attention to brain injury and its causes as discussed above, and the scant consideration for the civil right of individuals to protect their own persons.

## Progression from Motorcyclists

Victoria passed in 1960 the world's first legislation to compel motorcyclists to wear helmets. It was also a time of falling casualties, deaths of motorcyclists having halved over the previous five years. Though their death rate was much higher than occupants of cars, motorcyclists were mainly young men [59], the group which also has the highest rate of accident as car drivers. Despite voluntary wearing of helmets having reached 56 per cent, it was simply assumed that motorcyclists could not be responsible to protect themselves. Though proven efficacy is an obvious requirement for any safety measure, the Government presented no scientific evaluation. The minister merely said the police had been experimenting with helmets and "the Police Department and other organisations are now satisfied that the wearing of protective helmets will prevent deaths" [60]. It was assumed, perhaps by false analogy with helmets that protect workers from small fast-moving objects, that helmets would reduce brain injury.

Motorcycle helmets might have seemed to be a compelling precedent for cyclists, but the statistical evidence of their value in reducing casualties in Australia is poor. Their main value might just be to reduce superficial injury, as per one scientist's comment: "In 1963 and 1964, we had a collection of some thirty motorcycle collisions and my recollection is that the only difference between riders wearing helmets and not wearing helmets was that while the incidence of concussion was similar in both wearers and non wearers, those not wearing helmets had lacerations to their scalp. So the only visible protective effect was that the helmet stopped soft tissue injury to the scalp"[61]. Thus, there was no sound basis for the assumption that standard helmets would protect against brain injury. That an innovative measure of unproved efficacy could be passed into law without question might perhaps be attributed to motorcyclists being a minority with a high rate of casualty, and to a dread of brain injury.

Empirical studies have since claimed to show benefits from motorcyclists wearing helmets. In 1964, the Australian Road Research Board concluded, from examination of statistics before and after legislation, that it had reduced the risk of death in Victoria by two-thirds, but the study lacked data for some important variables and had no basis in mechanics of brain injury taking account of angular acceleration [59]. When the Australian Government was asked in 1994 to provide the evidence of efficacy of motorcycle helmets that supported its policy of compulsory wearing, it did not cite anything from Australia. Instead, it chose to cite an American study which estimated that helmets are 28 per cent effective in preventing fatalities to motorcyclists involved in accidents [62]. As well as being narrowly based, that study did not allow for an effect suggested by Davis, namely that helmeted motorcyclists might feel safer, ride a little less carefully and therefore have more accidents, in which other road users may also be injured[63]. Davis's suggestion is supported by detailed data for Britain, where compulsory wearing of motorcycle helmets was introduced in June 1973. Motorcyclists and pedestrians they collided with did not enjoy the decline in deaths and serious injuries that other road users experienced from 1972 to 1975, even after making allowance for an increase in motorcycling. Claims have been made that death rates of motorcyclists increased after the repeal of helmet laws in some states of the USA, but Davis noted that the main evidence for this was a graph of fatality rates across states, whether they repealed the law or not, and the rate of increase was greater in states that *did not* repeal their laws.

Corner et al. stated that there was evidence that motorcycle helmets of full-face design with face bars and shells made from smooth fibreglass offer some protection from rotation [48], but bicycle helmets are not so designed. In any case, Donald Simpson argued in 1996 that "The pros and cons of full-face helmets for motorcyclists need further consideration. More fundamentally, there is a need to know whether more deaths from diffuse brain injury could be prevented by helmets with different capacities to absorb energy. It is disconcerting that John Lane, pioneer in the evaluation of helmet benefits, has found no convincing evidence in the percentage of lives saved by motorcycle helmets in the last 30 years, despite much work on helmet design. This may well express the limitations of modern helmets in reducing rotation acceleration after head impact, the importance of which Cairns and Holbourn emphasized some 50 years ago" [14].

## Prior Encouragement

Of the Australian states, Victoria was the most active in encouraging the use of bicycle helmets before legislating to make it compulsory. Promotion of voluntary wearing started there in 1980 with safety education courses in schools, bulk purchasing of helmets and advertising which exhorted mothers to buy them for their children. A major publicity campaign was conducted in 1984 and is described in detail by Wood and Milne [64]. Surgeons of the RACS were active in pressing the Government to promote the use of helmets [65]. The Australian Medical Association [66] and the National Health and Medical Research Council (NHMRC) [67] added their support. Voluntary wearing increased and, at the urging of the RACS, the Government of Victoria announced in 1984 its intention to make it compulsory.

These actions were taken without scientific verification of the efficacy of helmets; in 1988 Wood and Milne stated that "the incidence of bicycle helmet use has not yet reached a sufficiently high level anywhere in the world for a scientific examination of helmet effectiveness in injury reduction to be undertaken" [64]. The Government of Victoria (1985) had made the same statement in 1985 in its submission to the federal parliamentary committee that recommended compulsory helmets (at page 1031), but it continued to promote the wearing of them and most other state governments followed Victoria's lead.

## Efficacy of Helmets

Long before the Prime Minister's announcement, it would appear that the public and politicians had taken the efficacy of bicycle helmets for granted. Because it was well known that helmets could protect the skulls of soldiers and miners from damage by light fast-moving objects, their efficacy against severe brain injury to cyclists would have seemed obvious. Indeed, before the parliamentary committee of 1985 had received any testimony on efficacy, it expressed its belief that all cyclists should wear helmets to increase safety. In support of its subsequent recommendation of compulsory wearing it used evidence of efficacy from only one study, a 1984 version of Dorsch et al. [58]. That study estimated from statistics for self-reported injuries to members of bicycle clubs up to 5 years earlier that the risk of death from head injury was considerably reduced for helmeted cyclists, but the sample was small and did not include any deaths. Reporting bias and a need for further research were acknowledged in the study. Further, in her own evidence to the committee (at page 901A), Dr Dorsch emphasised the need for care in using an estimate in the study that people wearing good, hard helmets were 19 times less likely to die, saying: “That was a hypothetical procedure based largely on an adult group of cyclists” and warning against generalising the findings to young bicyclists. Yet the committee's report cited the 19 times estimate without qualification, adding that the Dorsch study had “received almost universal acceptance by bicycle groups who have been working for many years to have helmets widely accepted” and “we all know that fatalities are occurring as a result of not wearing helmets” [3].

The Child Accident Prevention Foundation, a body founded in 1979 out of concern by pediatric surgeons who wanted to prevent accidents rather than just see their results, made a telling submission which argued that bicycle helmets should be worn by cyclists of all ages [evidence pages 628-637]. It posed the question: Why bicycle helmets? and then added that the answer is obvious to all safety conscious people, but “the facts supporting this assumption are not easily obtainable in the research literature”. By 1989, just before the Government decided to introduce compulsory wearing of bicycle helmets, an officially commissioned survey showed that public support for it was 92% for children and 83% for all riders [68]. Clearly, the Government’s confidence in the efficacy of helmets was based on little more than everybody knew it. A saying of cowboy philosopher Will Rogers is apposite: *“The trouble isn’t what folks don’t know; it’s what they do know that ain’t so”*.

Official verification of the efficacy of helmets is an obvious requirement to support legislation that compels their use. As noted above, the mandatory standard is inadequate to do this and research has shown there is no guarantee that soft helmets that comply with it can protect the brain at all; indeed, they may increase diffuse axonal injury. The 1985 Federal Parliamentary committee which recommended compulsory wearing of bicycle helmets complying with a mandatory standard seemed too easily convinced of their efficacy. Before it had received all testimony on this matter, it expressed its belief that all cyclists should wear helmets to increase safety. This perhaps reflects the submission of the then Federal Office of Road Safety[2] (FORS), which described helmets as “the principal means of reducing casualties”, but which it was unable to substantiate later [69].

The official response to an inquiry for the rationale for compulsory wearing cited six reports in support of it [70].The first two were those of inquiries by parliamentary committees in Victoria in 1986 and 1987 [4] and in New South Wales in 1988 [71]. Both assessed that cyclists were at great or worsening risk and recommended compulsory helmets. For evidence of efficacy, they simply relied on a decline in hospitalised head injuries to cyclists while the wearing of helmets was increasing in Victoria in the 1980s. The decline was attributed to helmets, but data in the 1987 report of the Victorian inquiry and represented in Figure 2 (reproduced from Curnow [72] with kind permission of *Health Promotion Journal of Australia*) show a similar trend for pedestrians. This suggests that factors which reduce injury

[2] Federal Office of Road Safety, subsumed into Australian Transport Safety Bureau (ATSB) in 1999.

to road users in general brought about the decline. It is not evidence of the efficacy of helmets to protect against head injury in general, much less against that to the brain.

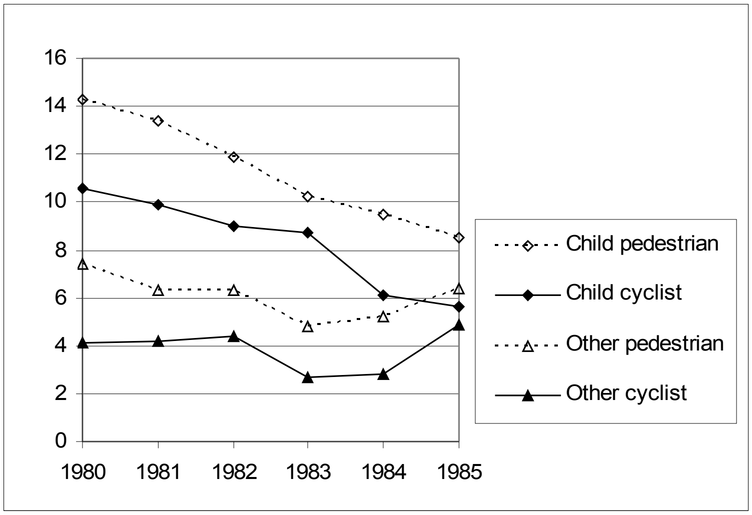


Figure 2. Most severe injury, per cent to head, Victoria.

The third report, a cost benefit analysis made by VicRoads in 1989, merely assumed the efficacy of helmets in preventing injuries, fatal and hospitalised. The fourth and fifth reports also do not deal with efficacy, but with the incidence of injuries in the ACT [73] and Western Australia [74]. The report from Western Australia notes that its data did not include enough wearers to assess with certainty whether head injuries were less common or less serious when a helmet was worn, but it then inconsistently recommends that the use of helmets should be promoted! The sixth report was that by Corner et al. [48]. Responses to inquiries in 1997 showed that no government in Australia, federal or state, made the necessary verification of the efficacy of helmets before legislating for compulsory use [75]. Governments cited studies which associate use of helmets with lower incidence of head injury, but none comprises a scientific assessment of efficacy against brain injury.

Federal authorities have not been diligent to review the policy of compulsory wearing against new knowledge. A 1994 report by the NHMRC on football injuries of the head and neck [54] cited studies of the efficacy of bicycle helmets, including Dorsch et al. [58] and Thompson et al. [42], but, unlike the Australian Transport Safety Bureau (ATSB), it 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 an increase in diffuse brain injury, but neither ATSB nor other authorities with responsibilities for bicycle helmets considered the implications [76]. Similarly, no cognisance was taken of medical opinion, given in evidence to an inquest into a death in a trotting accident, that the bicycle-type helmet which the victim wore had not protected her from diffuse brain injury [77]. Indeed, the authorities did not know of the NHMRC report or the inquest until this writer brought them to their attention.

In 2000, ATSB belatedly attempted to establish the efficacy of helmets by making a meta-analysis of 16 selected case-control studies [57]. The meta-analysis contains no discussion of scientific knowledge of brain injury, but it claims to provide clear evidence that bicycle helmets reduce the risk of it and fatal injury. A 2003 paper by Curnow rebuts the claim as it relates to injury to the brain, and therefore fatalities [78]; consequently, compulsory wearing still lacks a basis of verified efficacy.

Curnow similarly rebuts a claim based on the five major studies included in the meta-analysis, that all types of bicycle helmet can reduce injury to the brain [79]. The claim appears in the Cochrane Review *Helmets for preventing head and facial injuries in bicyclists* [80] and in the meta-analysis. Debate on this claim continued through 2006 in *Accident Analysis & Prevention*, with Hagel and Pless, Cummings et al. and Curnow contributing [81-84]. One point in the debate is that all of the studies used in the Cochrane review are of the case-control type, not randomised controlled trials, which are the nearest approximation to a scientific experiment when human beings are the subjects. Randomised controlled trials therefore are more reliable than other studies and are the normal standard for use in Cochrane reviews. ATSB has not entered the debate to defend its meta-analysis. By default, it has thereby relinquished any claim to the scientific validity of it. Yet ATSB continues to advise government that bicycle helmets substantially reduce the risk of brain injury to cyclists, and to advocate increased use of them [85]. And the Federal Government's assertion that the mandatory standard ensures the necessary head protection for cyclists has not been qualified [86].

## Effects of Legislation

In 1989, Australia had a unique opportunity to measure accurately both the efficacy of compulsory wearing as a policy and that of helmets in mass use. This could have been done by introducing compulsory wearing as a controlled social experiment. To do that, the large increase in wearing of helmets brought about by compulsion would be monitored and compared with changes in participation in cycling and in casualties, injuries to the head and brain in particular. To obtain the most robust statistics for analysis, the experiment would be on a nationwide scale. Therefore, the relevant laws of all states and territories would need to come into full operation at the beginning of a calendar year, the period for which statistics for casualties are collected, and changes which could introduce confounding factors into statistical analysis would be avoided as far as practicable.

The opportunity was missed. Federal authorities saw no need to confirm the efficacy of helmets and did not ensure uniformity in legislation and detailed monitoring of cycling and casualties. Their complacency of course reflected the general confidence in the efficacy of helmets on the part of the public, politicians and many cycling organisations. As a result of varying political factors, the helmet laws came into operation on five different dates: some at the beginning and others halfway through a calendar year; some at later dates for children than adults, who were supposed to be role models; and enforcement was delayed in some states.[3] Other changes to traffic laws came into force at or near the same time as compulsory

[3] Dates of introduction of legislation and its enforcement were: Victoria introduction and enforcement on 1 July 1990; NSW introduction and enforcement on 1 January 1991 for cyclists aged 16 years and older, and on 1 July 1991for children; Queensland introduction on 1 July 1991and enforcement on 1 January 1993; Western Australia introduction on 1 January 1992 and enforcement on 1 July 1992; South Australia introduction and enforcement on 1 July 1991; Tasmania introduction and enforcement on 1 July 1991; ACT introduction and enforcement on 1 July 1992; Northern Territory introduction and enforcement on 1 January 1992 for cyclists

helmets, in Victoria in particular. Also, practices in collection and treatment of statistics for injuries varied from state to state and from time to time. Relevant data on the effects of the legislation on participation in cycling and casualties are therefore patchy, but using what are available, the effects of the helmet laws in Australia are estimated here, and an economic evaluation is mentioned.

## Discouragement

Though it was known that compulsion to wear a helmet could discourage cycling [3], no national monitoring for it was done, but in most jurisdictions (percentages of total population shown in Table 1, second column) surveys made before and after the helmet laws, mainly to measure compliance with them, found declines in cycling/numbers of cyclists. The measured declines are shown in Table 1 (reproduced from Curnow [74] with kind permission of *Health Promotion Journal of Australia*), as follows.

**Table 1. Declines in cycling, Australia**

| State/territory | % | Class of cyclist | Decline pre-to post-law |
|---|---|---|---|
| New South Wales | 33 | Children <16 | 36% in 1st yr of law, 43% by 2nd yr |
| Victoria | 25 | Children Teenagers | 36% in 1st yr of law in Melbourne<br>46% by 2nd yr, in Melbourne |
| Queensland | 19 | Schoolchildren | > 22%, in 1st yr of law |
| Western<br>Australia. | 11 | Schoolchildren<br>All crossing 2 bridges | 20%, 1991-93; > 50%, 1991-96<br>38% on Sundays, in 1st yr of law |
| South Australia | 8 | Schoolchildren | 38%, 1988-94 |
| Tasmania | 2 | No data | No data |
| ACT<br>Nthn Terr. | }3} | All on bike paths<br>Children, teenage | 33%, 1st yr week days,<br>50% weekend 45% in 1st yr |

In Victoria, surveys were conducted at 64 sites in Melbourne in May of 1991 and 1992 and compared with a similar survey of child bicycling at those sites in May 1990, before the helmets law in July. In NSW, surveys were made at 39 road locations in April 1991, before the helmets law applied to children from July of that year, and in April 1992 and 1993. Efforts were made to make the surveys representative. The results of smaller surveys elsewhere are broadly consistent with NSW and Victoria. Giving due weight to those two states, which contain 58 % of Australia's population, the decline in cycling by children in Australia is estimated at 40%. The data are insufficient to make a similar estimate for adult cyclists, but 29% fewer were observed in Melbourne after the first year of the law [87] and all-age cycling declined in Western Australia and the ACT as shown. Also, national censuses show that in the five states with helmet laws on census day in 1991, 39798 persons got to work by bicycle, 47% fewer than the 73800 in 1986 [88] – a reversal of the rising trend shown in Figure 1 above.

In a submission to a committee of the Parliament of Western Australia which reviewed the helmets law in that state in 1994, the Federal Office of Road Safety acknowledged that cycling by children had fallen in Victoria, NSW and Western Australia but argued that this

aged over 17 and on 1 July 1992 for those younger.

was not a proven result of helmet laws and that cycling by adults mostly increased [89]. The argument is examined here.

In Victoria, surveys measured *usage* by comparing numbers of cyclists counted and the times taken to ride through marked areas in May 1990, just before compulsory wearing, and again in May of 1991 and 1992 [89]. The number and usage of teenagers fell by 46% and 44% respectively by 1991. The number of adults fell by 29%, but change in their usage was not measured because they were not timed in 1990. FORS claimed an increase for adults by comparing usage after compulsory wearing with that measured in 1987/88, disregarding both a caution by the authors of the surveys that the comparison is unreliable because the earlier survey was done at a different season 3.5 years earlier, and the rising trend in cycling before 1990. The claim is wrong.

For NSW, FORS said that in the first year of the law the number of children riding fell by 36% and adults by 14%, but that adult riding increased in the second year to 1991 levels (1993 was 1% higher than 1991). This comparison is wrong because the helmets law applied to adults from 1 January 1991, but not to children until 1 July. Hence, the 36% fall for children, from April 1991 to April 1992, was pre-law to post-law, but the 14% fall for adults in the same period was wholly after the law and was not a measure of its effect. Neither was the 1% increase from 1991 to 1993.

For Western Australia, FORS cited *Heathcote* [90] to claim that the law had little effect on the numbers of commuting and recreational riders. But FORS did not acknowledge that the supporting data are from only three sites for two hours one day a year and that *Heathcote* also recorded a decline of 38.3%, pre-law to post-law, in cyclists crossing the Narrows and Causeway bridges on Sundays. For Australia as a whole, FORS concluded that the decline in cycling was an "initial fall" with some indications that bicycle usage may be returning to pre-law levels, but the surveys needed to support this view were not done. The investigator who found the sharp declines in cycling in Victoria is reported to have said: "We've been unable to secure the funds to repeat our counts so we just don't know whether the numbers of teenagers ever returned" [91].

Less participation in cycling can have many adverse effects. At the community level, it may change the behaviour of motorists so as to increase the risk of accident to cyclists. Motorists seeing fewer cyclists may make less allowance for them (the converse of safety in numbers). An analysis of Australian data estimated that a halving of cycling would increase the risk per kilometre by 50% [92]. Seeing cyclists wearing helmets might also change the behaviour of motorists. In England, measurements of 2,500 overtaking events found that drivers passed significantly closer to a cyclist (on average 8.5 cm) when a helmet was worn than when it was not [93]. It would seem that motorists think that wearing a helmet makes a cyclist less vulnerable.

Less cycling also results in loss of the benefits of the exercise for health. The British Medical Association estimated that the benefits of cycling for health outweigh the loss of life due to accidents [94]. Large-scale studies in Denmark associated physical activity such as cycling with lower risk of death and estimated that bicycling to work reduced it by 40% [95, 96]. The adverse effects of helmet laws on health may be greater for children, girls in particular. In NSW, surveys showed that 455 girls cycled to high school in April 1991, just before the helmets law, but only 186 a year later and 106 in April 1993, a decline of 77 % [97]. The helmet laws surely would be contributing to the prevalence of obese children.

Two effects of reduced cycling are peculiar to children. One is that they do not gain experience when young in using roads and being responsible to take care of other road users. Then, in their late teens and with little road sense, they are in charge of a powerful and potentially lethal motor vehicle. Also, people who have not had experience of cycling as a child are less likely to be aware of the needs and vulnerability of cyclists and the special care of them that is required.

At a time when much of the world is concerned that global warming may be occurring and human use of fossil fuels is contributing to it, it would seem to be unwise to adopt or maintain policies which discourage cycling, the most energy-efficient means of transport.

## Serious Casualties

The total effect of compulsory wearing obviously depends on the efficacy of helmets, or the lack of it. As well, official advocacy of helmets and legislation to compel their use might well engender an unwarranted sense of security among cyclists, leading them to take more risks; after official campaigns to increase wearing in Victoria in the early 1980s, a study found that teenagers believed helmets would save them in a serious accident with a bus or a truck [98]. And for children riding on uneven surfaces, the weight of a helmet is likely to reduce their stability [99].

**Table 2. Serious casualties to road users, Australia 1989 – 1993**

| Year | Total road users | | Pedestrians | | Bicyclists | |
|---|---|---|---|---|---|---|
| | Adult | Child | Adult | Child | Adult | Child |
| 1989 | 27323 | 3938 | 2882 | 1083 | 898 | 760 |
| 1990 | 23921 | 3371 | 2664 | 1050 | 950 | 707 |
| 1991 | 21824 | 2817 | 2325 | 866 | 768 | 502 |
| 1992 | 20734 | 2752 | 2316 | 862 | 775 | 464 |
| 1993 | 21325 | 2634 | 2262 | 752 | 805 | 442 |
| Change, 1989-93 | -24% | -33% | -22% | -31% | -10% | -42% |

Table 2 (reproduced from Curnow [74] with kind permission of *Health Promotion Journal of Australia*) shows numbers of serious casualties (fatal and hospitalised) to adults (16+) and to children from 1989, the last year before any helmet laws, to 1993, the first year after all were in force.

Clearly, adult cyclists did not share commensurately in the general improvement in road safety. Nor did child cyclists; the fall in casualties to them was about the same as the decline in participation. No benefit from compulsory wearing of helmets is evident; rather, it would appear that the risk to cyclists increased. Indeed, from studies in Australia and New Zealand *Elvik and Vaa* estimated that mandatory wearing of helmets increased the risk of injury per kilometre cycled by 14% [100].

## Head Injury

An analysis of statistics before and after helmet laws in New South Wales and Victoria, found no decrease in the risk of head injury, fatal and hospitalised [101]. Similar data on brain injury are not available for Australia, but the occurrence of the most severe may be approximated by statistics for fatal head injuries. For Australia, these are available only for alternate years, in the Fatality File published by the Australian Transport Safety Bureau (ATSB). Table 3 (reproduced from Curnow [79] with kind permission of *Accident Analysis & Prevention*) is compiled from it.

**Table 3. Deaths of road users in Australia, in total and by head injury**

| | Pedestrians | | Bicyclists | | All road users | |
|---|---|---|---|---|---|---|
| **Year** | **Total** | **Head** | **Total** | **Head** | **Total** | **Head** |
| 1988 | 542 | 233 | 86 | 40 | 2868 | 1085 |
| 1994 | 346 | 145 | 56 | 28 | 1787 | 631 |
| Change 1988/94 | -36% | -38% | -35% | -30% | -38% | -42% |

The table shows that from 1988, before the first helmet laws, to 1994, when all were in force in Australia, deaths of all road users by head injury decreased by 42% and pedestrians by 38%, but cyclists by only 30%. No benefit from the helmet laws is evident; indeed, increased risk to cyclists is indicated when account is taken of the decline in their numbers. Available data are inadequate to estimate any trend in chronic disability from non-fatal head injury. Even if its commonest cause, diffuse axonal injury of the brain, is diagnosed, it is typically not specified in statistics for road accidents as published by the Australian states.

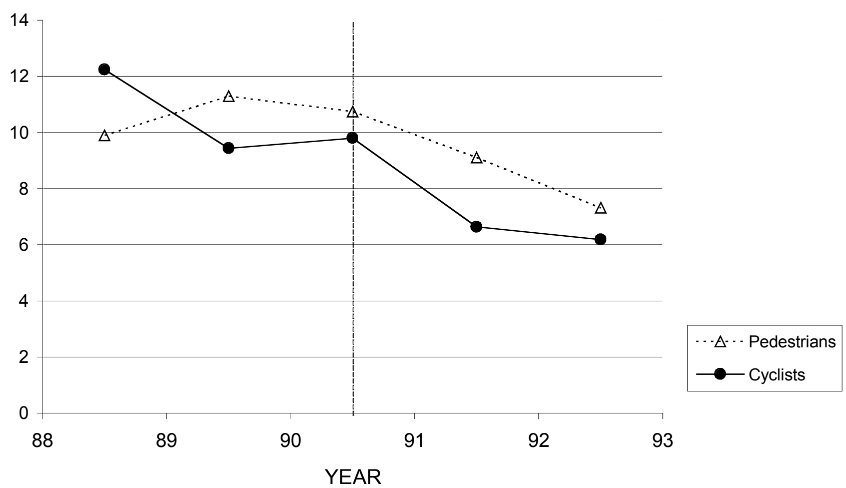


Figure 3. Per cent head injury, of accepted TAC no-fault claims, Victoria.

The above-mentioned submission by FORS to the Parliament of Western Australia cited decreases in head injury to cyclists in some states but made no allowance for general improvements in road safety or declines in cycling. For Victoria, it noted that in the first year of compulsory wearing, cyclists' claims on the Transport Accident Commission (TAC) for head injuries decreased by 51% compared to 24% for non-head injuries. In the second year, the respective decreases reached 70% and 28%. The submission ascribes the differences to increased wearing of helmets, but inquiries to the TAC have revealed a similar trend for pedestrians. This is shown in Figure 3 (reproduced from Curnow [74] with kind permission of

*Health Promotion Journal of Australia*). The vertical dashed line in Figure 3 shows the start of the helmets law on 1.7.90. It would appear that factors other than helmets were responsible for both declining trends.

## Wearing Rates of Casualties

Efficacy of helmets would be suggested if casualties had lower wearing rates than the whole population of cyclists. In Victoria, Vicroads proposed to increase the penalty for not wearing a helmet [102]. It noted that the rate of wearing after legislation was 75%, but 125 cyclists involved in accidents in 1999 were not wearers. As the number of wearers was not stated, further data were obtained from Vicroads and for NSW, Queensland and South Australia.These data, for 84% of Australia's population, are shown in Table 4 (reproduced from Curnow [74] with kind permission of *Health Promotion Journal of Australia*). In it, casualties are the sum of fatal and serious injuries whose wearing of a helmet was known, about 90%, and wearing rates by the population are as measured by survey.

**Table 4. Helmet wearing of cyclists who were casualties and whole population**

| State Year | Casualties, helmet worn | Casualties, not worn | Casualties, % worn | Population, % worn, year |
|---|---|---|---|---|
| Victoria 1999 | 198 | 51 | 80 | 75 |
| NSW, 1993 | 192 | 56 | 77 | 74, 83* (1993) |
| Q'land, 1994 | 441 | 136 | 76 | 67-89**(1993) |
| Sth Aust. 1994 | 67 | 4 | 94 | 86, 91* (1993) |

* child, adult ** range of primary and secondary school students and adults

The table shows that the wearing rates of cyclists who were casualties were no lower than the average of the whole population. This provides no evidence that wearing a helmet reduced the risk of casualty and suggests that it may have worsened in Victoria, but the penalty for failing to wear one there was increased.

## Economic Evaluation

An economic evaluation of compulsory wearing, excluding loss of health benefits of the exercise, was made in Western Australia [103]. It calculates a net present value of benefits in the range plus $2 million to minus $10.6 million and calls for a comprehensive national evaluation, which has yet to be done.

## Civil Rights

In liberal democracies, the powers of public authority are contained within law which is consistent with two basic beliefs of Western Christendom: the rational and organic nature of society and the transcendent value of the human person [104]. A balance exists between the right of the state to impose legal sanctions and the rights of the individual, including self-protection. J.S. Mill defined the balance in 1858 as follows:

> "The only purpose for which power can be rightfully exercised over any member of a civilised community, against his will, is to prevent harm to others. His own good, either physical or moral, is not a sufficient warrant. ... Over himself, over his own body and mind, the individual is sovereign." [105]

Mill went on to describe a proper office of public authority to guard against accidents:

> "When there is not a certainty, but only a danger of mischief, no one but the person himself can judge of the sufficiency of the motive which may prompt him to incur the risk: in this case, therefore he ought to be only warned of the danger; not forcibly prevented from exposing himself to it."

In Hitler's Germany, under the doctrine "Law is what benefits the people" individual rights and freedoms were subjugated to the common good, as evaluated by the state, and the balance as Mill had defined it was destroyed. The Universal Declaration of Human Rights, 1949 (UDHR) re-affirmed individual rights: freedoms to be limited only as necessary to safeguard rights of others. This established Mill's definition as an international standard.

Liberal democracies generally comply with that standard. They leave self-protection largely to individuals' instinct of self-preservation, the function of public authority being to assist by providing information and advice and setting safety standards for protective devices. In general, standards are enforced upon suppliers whose products may affect the safety or health of others; but individuals remain free to take their own risks – smoke, enjoy dangerous sports or refuse medical treatment. The role expected of the state is to inform them about the consequences.

Australia has a system of universal health care which is financed by government. Some people argue that government is thereby entitled to constrain the behaviour of individuals so as to minimise its cost, but health authorities have shunned making medical treatment compulsory even where, as with vaccination against contagious diseases, other people at risk might benefit. The compulsory use of bicycle helmets is an exception. Its officially stated purpose being to reduce the public cost of health care, its character is a preventive medical treatment, but it is not subjected to similar scrutiny as other means of effecting medical treatment, namely, drugs and therapeutic devices. In Australia, as in most countries, competent and independent authority evaluates the efficacy and safety of drugs and therapeutic devices, having regard to all relevant knowledge, and monitors their use and published reports about them. If adverse effects or dangers in their use come to light, they are withdrawn from the market. As noted above, responsible authorities failed to consider the implications of a report of the NHMRC which warned that the wearing of helmets may result in an increase in diffuse brain injury.

Paradoxically, while the legislation was taking away the right of individuals to choose whether to wear a helmet, their right under the common law to decide upon other preventive medical treatment to protect their health was being strengthened. A 1990 guide to the law noted that over the previous twenty years it had "increasingly been recognised that patients have the right – indeed the responsibility – to decide for themselves what medical tests or treatment they will have" and doctors have a duty "to give patients sufficient information to enable them to make their own decisions about the treatment that is offered to them" [106]. Superior courts continued to strengthen individual patients' rights. In 1992, England's highest court upheld the right to refuse medical treatment, as follows: “The patient's interest consists of his right to live his own life how he wishes, even if it will damage his health or lead to his premature death. Society's interest is in upholding the concept that all human life is sacred and that it should be preserved if at all possible. ... in the ultimate the right of the individual is paramount” [107]. Subsequently, the High Court of Australia acknowledged, in a case concerning medical treatment “the paramount consideration that a person is entitled to make his own decisions about his life” [108].

Reducing casualties is the laudable motive of compulsory self-protection of road users, but the subjugation of individual rights and freedoms for the supposed common good has set Australia on a dangerous path. Pressed to its logical extreme, any activity that increases the public cost of health care could be banned, such as smoking, any dangerous sport, over-eating – the list goes on. As the eminent judge Louis Brandeis warned Americans in 1928: “Experience should teach us to be more on our guard to protect liberty when the Government's purposes are beneficent. The greatest dangers to liberty lurk in the insidious encroachments by men of zeal, well meaning but without understanding”[109]. Forty years on, Justice Lionel Murphy of the High Court of Australia gave a similar warning:

> “Every generation has to fight over and over again the battle for our fundamental rights and liberties, and this generation has to do that also. In recent times, almost every one of our fundamental rights and liberties has been either trampled on, whittled away, challenged or ignored”[110].

Nevertheless, the Australian public has hardly questioned the usurpation of the democratic right of individual road users to choose how to protect themselves.

## Conclusion

People have been preoccupied with injuries to the brain and how to protect it at least since it, and not the heart or other organ, has been recognised as central to our consciousness and sentience. Indeed, following Descartes’s dictum *Cogito ergo sum*, our brain is the centre of our being. Throughout history, helmets to protect it have formed part of the armour of warriors, but the injuries that these prevent are only the lesions that result from penetration or other fracture of the skull. Though the consequences of these can be dire, including death, the brain injury which results in the coma and dementia that make us less than fully human was unknown until fifty years ago.

Since the 16$^{th}$ century at least, the medical profession, and surgeons in particular, have properly been concerned to understand brain injury and its causes. A great mystery was how concussion or coma followed by chronic dementia or death could occur without damage to the skull or no lesions in the brain at autopsy. Another was why lesions seemed to occur both near a blow to the skull, which might remain undamaged, and at its opposite side. To explain it, Mortgagni proposed in 1766 the theory of coup and contre-coup: when the head is struck, the skull moves towards the brain, and strikes it. The brain then bounces back in the reverse direction to strike the skull on its opposite side, where, oddly, the injury was often more severe. As this early attempt to apply knowledge of mechanics to medicine was predominant for two centuries, it ranks as a great contribution to understanding brain injury. But it was conceived before scientific medicine as we know it. The scientific understanding which Holbourn brought to bear in the 1940s and the findings of subsequent research in the $20^{th}$ Century have thoroughly discredited the old theory. Yet some medical practitioners still give it lip service, if not credibility, and it would seem to be influential in the thinking of the designers and promoters of helmets – their universe is still geocentric.

The new theory of Holbourn, which attributes brain injury where the skull is undamaged to angular acceleration, has proved to be doubly valuable. The more accurate and detailed observations of so-called contre-coup injuries that have been made in recent times have shown that they rarely occur on the opposite side of the brain from coup injuries. Their location depends more on the shape of the brain and the internal surface of the skull, so that they mainly occur in the frontal and temporal lobes and in the sylvian fissure, independent of the site of impact. This cannot be explained by the old theory, but is entirely consistent with the new. More impressively, the new theory provides a mechanism of diffuse injury to the axons of the brain. Though its symptoms such as concussion, coma and chronic dementia were well known in Holbourn's time, the diffuse axonal injury which is their cause had not been defined. Upon defining it, Strich immediately explained it according to Holbourn's theory, an explanation which scientific research since then has supported.

Though the theory that linear acceleration is the main cause of brain injury has been discredited in scientific circles, it still holds sway in the minds of many whose interest in head injury is prevention. Prominent among these are surgeons who see the dire results of serious brain injury and are concerned to do more than alleviate it. The theory also predominates in the technology of helmets for motorcyclists and cyclists. It is convenient for both medical professionals and the helmets industry to adhere to that theory because it appears to offer a simple solution to the complex problem of protecting against brain injury. It is understandable that such a solution is attractive to medical practitioners, because they are committed to improving health. But wanting helmets to be efficacious does not make them so, and by disregarding current scientific knowledge well-meaning practitioners may infringe the injunction of Hippocrates to do no harm. This would seem to be the case with the introduction of compulsory wearing of helmets in Australia.

Designing helmets to reduce linear acceleration suits the helmets industry which has, in effect, made a huge investment in the theory that it is the main cause of brain injury. Because the theory is widely accepted, claims that helmets prevent injury or even save lives are plausible enough to persuade the public to buy them and politicians to pass laws to compel their use, creating an assured market for them. Finding practicable means to reduce angular acceleration is an unsolved problem, however; there is no money in it for industry.

In Australia, both the medical profession and the helmets industry have been unduly influential in the introduction of compulsory wearing of helmets. In the 1980s conditions were right for this to happen, laws to compel use of seat belts in cars and motorcycle helmets having been in place for a decade. The Australian public and politicians have for long been greatly concerned about road safety and governments have become ever more intent on regulating individual behaviour to achieve unrealistic aims, such as zero road toll. Insufficient attention has been given to the social costs of such aims. For example, some politicians have claimed that compulsory wearing of bicycle helmets is justified if even one life is saved. The public and politicians have an exaggerated impression of the dangers of cycling; hence the introduction of compulsory wearing when the risk of serious casualty was falling. Their faith in the value of helmets for cyclists has never wavered. This is partly because the critical issue of protecting the brain from fatal and disabling trauma has been lost in a plethora of official utterances and statistics dealing with head injury in general, most of which is minor.

More important, the relevant science has not been applied to assess the efficacy of helmets to protect the brain, against diffuse injury in particular. The policy of compulsory wearing of helmets was introduced in Australia without proper scientific support and without making the most of the opportunity to test its efficacy in practice. The purpose of the policy is to reduce the medical and other public costs of bicycle accidents, but, in experience, the compulsory wearing of helmets has been counterproductive. Cycling, especially by children, has been discouraged, with loss of its many benefits, especially for health. Casualties, even deaths by head injury, have fallen less than commensurately with the declines in cycling and in casualties to other road users; this may be due in part to less safety in numbers. The civil liberty of cyclists to choose how to protect their own persons has been lost for no gain.

Clearly, a thorough investigation of the efficacy of helmets and effects of compulsory wearing in Australia is needed, preliminary to review of the policy, but authorities seem to be unwilling or unable to learn from experience and are resisting pressure to take such action. Though the policy of compulsory wearing has gone badly wrong, authorities still insist that the sun goes around the earth. Such attitudes have implications that are wider than bicycle helmets; they indicate a lack of scientific understanding among road safety authorities and a need for governments to take action to strengthen their competence.

There is also a lesson for other countries. Most countries of Europe may not need it; their experience of regimes that curtail individual liberty for some supposed common good has ensured that. The UK and Canada are showing signs of heeding the lesson, but the portents in the USA so far are not so hopeful.

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