HELMETS AND NECK INJURIES IN FATAL MOTORCYCLE CRASHES

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ABSTRACT

A common objection to helmet use is the fear that any benefit in preventing brain injuries may by offset by increased neck injuries, especially spinal cord injuries. A little known follow-on study to the so-called Hurt Study investigated this hypothesis in detail through the investigation and reconstruction of 304 fatally injured motorcyclists in 295 crashes in Los Angeles County with special emphasis on identifying head and neck injuries and their causes. Detailed layer-by-layer autopsy of the head and neck was performed in all cases in order to identify soft tissue injuries that are rare or go undetected in riders who survive. Injuries were coded using the 1990 version of the Abbreviated Injury Scale. Sixty motorcyclists (20%) had been wearing a helmet when they crashed. Helmeted riders, as a group, had generally been in more severe crashes, as evidenced by the much more severe below-the-neck injuries, especially to the chest and abdomen, so they might be expected to show more neck injuries. Helmeted riders were no more likely than unhelmeted riders to suffer spinal cord injuries. Nor were they more likely to suffer fractures of the cervical spine or subluxation/dislocation injuries at C1-C2. They did have more subluxation/disclocation injuries in lower cervical (C3-C7) region and more frequent hemorrhage in the carotid sheath. Both helmeted and unhelmeted motorcyclists in these fatal crashes showed a high frequency of soft tissue neck injuries such as hemorrhages in the carotid sheath, hemorrhages surrounding the phrenic nerves or the brachial plexus, or hemorrhages surrounding the vertebral arteries, all of which seem to be rare in non-fatal crashes.

INTRODUCTION

The neck is a relatively slender, flexible, vital structure that connects the larger masses of the head and body. It is rarely contacted directly in motorcycle accidents, though the injuries can be extreme when a motorcyclist rides into a chain anchored across his path. Most neck injuries result from indirect loading. When collision forces act differently on the head and body this can transmit forces – and sometimes extreme forces – to the neck, resulting in injury. Whether helmets themselves cause neck injuries that would not occur in the absence of a helmet has long been a concern, at least to some motorcyclists.

The origin of the helmets-break-necks hypothesis is not clear. One possible source is a report from New York state in the first year after instituting a mandatory helmet law (Negri, 1969). Comparing police reports from 1966 (before the law) to 1967 (after the law) the author found that serious head injuries declined from 116 per 1000 crashes to 69 per 1,000 while serious neck injuries doubled from 3 to 6 per 1000 crashes. That is, 47 riders per 1,000 crashes benefited from head injury prevention while 3 per 1,000 suffered a neck injury. In 1964, Fenner raised the possibility that the face guard on helmets for American football could act as a lever arm to rotate the rear edge into the back of the neck and thereby cause neck injury – a sort of "karate chop" mechanism.

However, a number of other studies have failed to find neck injuries significantly over-represented or underrepresented among helmeted riders, suggesting that helmets appear to have no clear effect on neck injuries one way or the other (Hurt et al, 1981, pp. 301-303; Orsay et al., 1994; Liu et al., 2009; Crompton et al., 2012).

Krantz (1985) was alarmed by the coincidence of helmet use and disruption of the craniocervical joint in five of 135 fatally injured motorcyclists he examined, all wearing open face helmets. He therefore argued that helmet weight contributes to the risk of lethal neck injury. The effect of helmet weight will be examined in this paper.

The frequently cited study by Goldstein (1986) badly misused the Hurt study database to conclude – erroneously – that helmets increase the risk of neck injuries above about 13 mph. The less serious of two major errors in that paper is one of confusing motorcycle crash speed with the "normal component of velocity." The normal component of impact velocity is the component of impact velocity perpendicular to the surface of the helmet (as compared to the velocity component parallel to the helmet surface.) Crash speed and the normal component of impact to the helmet are the same only if the rider runs perpendicularly into a barrier, which is extremely rare. On the other hand, if a helmet free-falls onto horizontal pavement from the normal ride height of 4½ feet, the maximum downward speed of impact with the horizontal pavement would be no higher than 11.6 mph. Whether the motorcycle's forward speed when the crash occurs is 1, 10 or 100 mph or anything in between, the normal component of impact velocity would be no more than 11.6 mph.

However, the worst error in Goldstein's paper is the mysterious origin of the numbers that lie behind the conclusion that above about 13 mph helmets increase the risk of neck injury. Hurt et al simply did not record the "normal component of impact velocity" for any unhelmeted riders – or for about 90% of helmeted riders. The question about normal component of impact velocity to the helmet surface appeared in the *helmet* section of the data form (Hurt et al., 1981b, pp. 34-35, questions 25 & 37). Because of that, "normal component of impact velocity" was coded "not applicable" for unhelmeted riders since they weren't wearing a helmet. And, because the question turned out to be so devilishly difficult to answer, it was coded "unknown" for about 90% of helmeted riders. Thus the source of the numbers for "normal component of impact velocity" in Goldstein's paper is unclear, though it is clear the numbers did not come from the Hurt study.

Weiss (1992) correctly used the same Hurt study database and concluded that neck injuries above the minor level were so infrequent that any helmet effect on neck injuries would have only a small effect on injury statistics and overall hospital costs.

One precaution should always be kept in mind whenever comparing helmeted and unhelmeted riders in fatal crashes: as a group, unhelmeted riders tend to die in less severe crashes than helmeted riders because an unlucky blow to the unprotected head can turn an otherwise minor crash into a fatal one. Motorcycle crash speed itself is a poor indicator of crash severity (Ouellet, 2013) and this is shown in Figure 1. The crash speed distributions for helmeted and unhelmeted riders are nearly identical. Figure 2 uses the severity of the most severe somatic (i.e., below-the-neck) injury as its measure of crash severity. Roughly one in six unhelmeted riders died in crashes where the worst below-the-neck injury was no worse than a scraped knee or broken toe. Sixty-three percent of helmeted riders died in very high severity crashes (Severe-Critical-Maximum injuries) compared to 50% of the unhelmeted riders. “Maximum” injuries are currently untreatable, such as torso transaction, rupture of the heart, decapitation, etc.

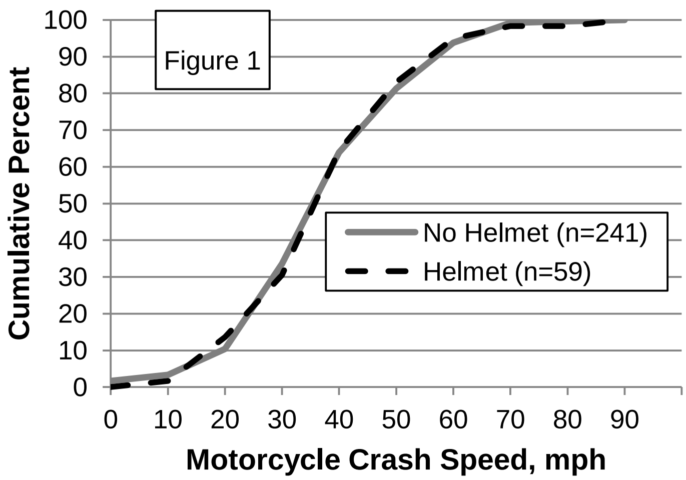
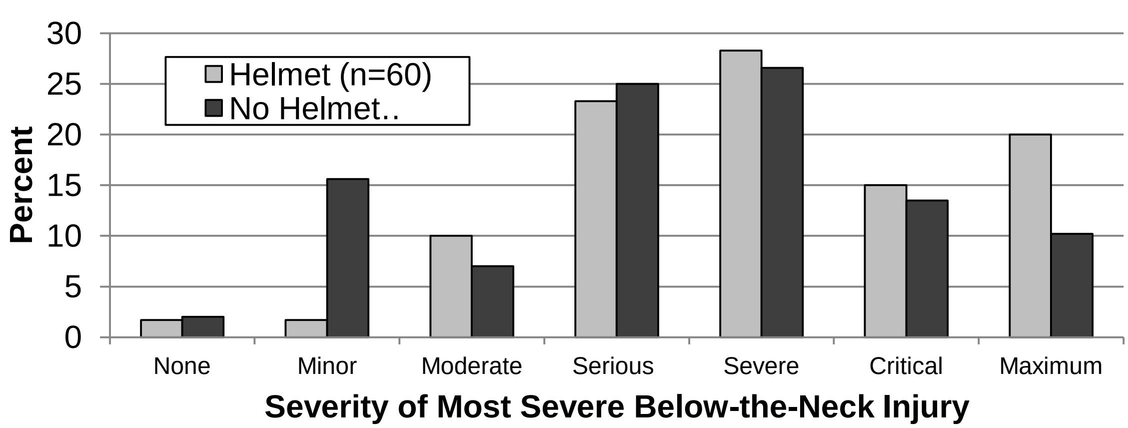


Figure 3 shows another way of looking at this disparity. It combines data from the Hurt study and the Thailand study (Kasantikul, 2002a, 2002b) to compare fatality rates among helmeted and unhelmeted riders over different levels of the most severe below-the-neck injury. For both groups, the fatality rate was about 0-3% for when the most severe somatic injury was below the “serious” level.

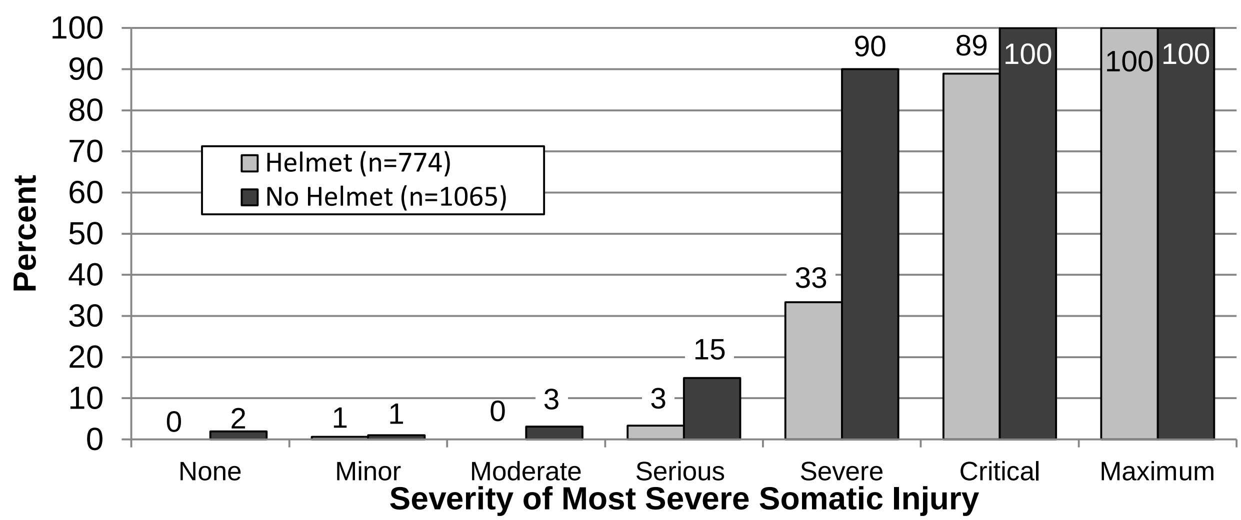
Figure 2. Distribution of helmeted and unhelmeted groups by most severe somatic (below-the-neck) injury.



The fatality rate was nearly 100% when the most severe somatic injury was at the "Critical" or "Unsurvivable" level. However, great divergence appears at the level of "Serious" and "Severe" somatic injuries, which involved a total of 236 cases – about one in seven.   In this Serious-Severe range, one-fourth of the unhelmeted riders (36 of 141) died compared to 4 of 95 helmeted riders (4.2%).

Because of the differences between helmeted and unhelmeted riders in fatal crashes, the results are presented separately graphs of 1) Riders in high severity crashes with Somatic AIS>3 (Severe-to-Unsurvivable) injuries; . 2) Riders in low severity crashes with injuries in the Somatic AIS≤3 (None-to-Serious) and, 3) all 304 riders

Figure 3. Probabilityof death as a function of the most severe below-the-neck injury among 1839 motorcyclists in the Los Angeles and Thailand on-scene, in-depth accident studies.



There are other caveats to remember. It should be no surprise that this paper will report more neck injuries than most papers for two reasons: 1) because these fatal crashes are, as a group, far more severe crashes than the great majority of motorcycle accidents and are therefore more likely to place severe injury-causing stresses on the neck, and 2) because these are fatal crashes, detailed dissection procedures to find even minor neck injuries were possible – something one could never do with riders who survive their crash and 3) we were looking specifically for any and all head and neck injuries.

METHODS

Accident notification

Tthe University of Southern California (USC) Motorcycle Accident Research team extended an existing cooperative agreement with office of the Los Angeles Chief Medical Examiner – Coroner (LACME) to receive notifications when a motorcycle

fatality occurred. A case was selected for investigation depending primarily on two factors: 1) that the motorcyclist died within 10 days of the accident and, 2) that enough evidence could be collected to develop a reliable investigation.
On-scene, in-depth motorcycle accident investigations were conducted for 295 crashes that killed 304 riders and passengers in Los Angeles County. On-scene investigations usually took place the same day the team received notification. Accident scenes almost always had "cleared" before USC investigators arrived. That is, police and other emergency personnel had completed their work and left the scene, vehicles had been towed and so on.

For each accident, all environmental factors, i.e., vehicle pre-crash paths of travel, including view obstructions, pavement irregularities, traffic conditions, conspicuous skids of pre-crash evasive action, post-crash scrape marks, etc., were recorded and photographed. Diagrams of the accident scene were drawn to show pertinent evidence and all skid and scrape distances, as well as all points of impact and points of rest. Examination and photography of the motorcycle was usually completed on the same day as the accident scene investigation, usually at a police tow yard. If another vehicle was involved in collision with the motorcycle, it was often inspected at the same tow yard as the motorcycle. In some cases – particularly hit-and-run crashes, the vehicle was never seen.

There was no preselection for any type of accident characteristic or factor, with one exception. Late in the project, the decision was made to acquire more accidents involving helmeted riders and to reject any more cases involving unhelmeted riders. The reason for this change was the unexpectedly low proportion of helmeted riders (about 18%). Thus, 15 of the last 54 cases (28%) were helmeted riders, representing an additional five helmeted riders in the total of 304.

Sixty riders wore a helmet; 51 of those helmets (85%) were examined. In a couple of these, the examination was limited to police photos taken at the accident scene. Accident-involved safety helmets were taken to the lab where they were weighed, visually inspected and photographed to show all externally visible surfaces, with close-ups of damaged areas. Notes and photos also documented accident damage such as the size of external impact areas, the type of impact surface the helmet had struck (impact signature characteristics often define the type of surface struck: tire rubber, painted sheet metal, window glass, asphalt pavement and concrete pavement all leave highly distinct markings that are readily distinguishable from one another.) Inspection of the external features of the helmet also included examination of the chin straps and retention system, for signs of stress or failure.

After external examination and photography, the helmet was disassembled by removing the energy-absorbing liner from the shell, then stripping the comfort pads from the liner. Liner density was measured. Areas of impact crush were measured to determine the residual crush depth and the area of crush damage and then photographed.

In the case of helmet ejection, investigators looked for evidence to determine the cause of ejection and whether the ejection occurred before, after or during a critical impact to the head.

Below-the-neck injuries were reported in a standard autopsy performed by LACME medical examiner. Neck injury information came from a detailed layer-by-layer dissection of the anterior and posterior neck and head. The brain and spinal cord was removed as a single bloc as part of the head-neck dissection and sent to a neuropathologist for detailed examination.

Injury information was coded in accordance with a system described elsewhere [23]. Briefly, each injury was described using a combination of six alphanumeric codes. The codes described, in sequence the injury 1) region 2) side 3) aspect (superior, lateral, etc.), 4) lesion type, 5) system / organ injured, and 6) injury severity (AIS). For example, an injury such as a bilateral hinge fracture of the medial fossa would be coded as “basal – bilateral – medial – fracture – skeletal – 3 (serious).

Injury severity was originally coded in accordance with the Abbreviated Injury Scale, 1980 revision, but later was recoded to conform to the 1990 revision of the AIS.

Accident reconstruction

Investigators reviewed and analyzed all the information to determine a wide range of factors, including how and why the crash had occurred, how the injuries had occurred and how the helmet had performed in the accident. For unhelmeted riders, investigators also attempted to make a determination of how a helmet would have performed if one had been worn. Photographs were a crucial element in the reconstruction, since they often helped to identify precrash actions (through skid marks – or lack of skids – along the precrash path of travel), the sequence and locations of contact during the actual collision, and so on.

Data recording and analysis

When the data form had been completely filled out, the case was sent to a second reviewer for quality control review and correction. The completed data was then reviewed, looking for errors of improper entries (such as speeds over 200 mph, or non-existent or nonsensical injuries.) When the errant coding entries had been corrected, the data was then processed using the Statistical Package for Social Sciences (SPSS).

Because, as Figure 1 shows, unhelmeted riders tend to die is less severe crashes than helmeted riders, the data are reported here in two way ways: 1) all 304 riders (which tends to show fewer neck injuries among unhelmeted riders), and 2) riders whose most severe somatic (below-the-neck) injury falls in the severe-to-unsurvivable range. This equalizes helmeted and unhelmeted riders by restricting comparisons riders who have been in crashes of roughly comparable severity.

RESULTS

High Severity Crashes

Figures 4 and 5 show the percentage of riders who suffered different types of injuries in the high severity crashes – those in which the most severe below-the-neck injury was coded as “Severe, Critical or Maximum,” using the Abbreviated Injury Scale. Figure 3 presents data for spinal cord and spinal column injuries. The expression “spinal column injury” is used here to refer to injuries of the architectural elements of the spinal column: vertebrae, intervertebral discs and the ligamentous structures that stabilize the column – but *not* to the spinal cord. The injuries tallied here are fractures, dislocations (in which displacement of the vertebrae remained visible at autopsy) and subluxations (in which the column has been displaced but returned to normal alignment, leaving evidence of injury such as ligament stretching, disc hemorrhage, etc.)

Injury rates in the high severity crashes illustrated in Figures 3 and 4 usually did not differ significantly. Two exceptions involved helmeted riders being significantly more likely to sustain hemorrhage in the carotid sheath and hemorrhage surrounding nerves (such as the phrenic nerve) or nerve plexes (such as the brachial plexus). Helmeted riders were also more likely to sustain fracture of C1 and C2, though the difference fell short of statistical significance.

By far the most frequently seen injury to the architectural elements of the cervical spine were subluxation injuries of C1 and C2. This usually showed up as hemorrhage in beneath ligaments (anterior and posterior longitudinal and cruciate ligaments and the ligatmentum flavum) as well as laxity and excess motion in the atlanto-occipital and atlanto-axial joints. Perhaps most important, spinal cord injuries did not differ between helmeted and unhelmeted riders.

Low severity fatal crashes

Low severity crashes are those in which the severity of the most severe below-the-neck injury falls into the none-to-serious range. “None” is self-explanatory. A very common “serious” injury below the neck would be an open or comminuted fracture of the tibia and/or fibula.

The neck injury rates for riders in low severity crashes are shown in Figure 6 (spinal cord and cervical spine) and Figure 7 (cervical soft tissues).

In these lower severity crashes, some injuries increased compared to the high severity crashes while other decreased or remained the same. For example, spinal cord injuries increased for helmeted riders but not for unhelmeted riders. C1-C2 fractures remained largely unchanged but C3-C7 fractures increased for helmeted riders though not for unhelmeted riders. Hemorrhage in neck soft tissues remained largely unchanged except that carotid sheath injuries and hemorrhage on nerve roots and trunks declined among helmeted riders to the point of not differing significantly from unhelmeted riders.

Figure 4. Spinal cord and spinal column injury rates for helmeted and unhelmeted riders in high severity crashes.

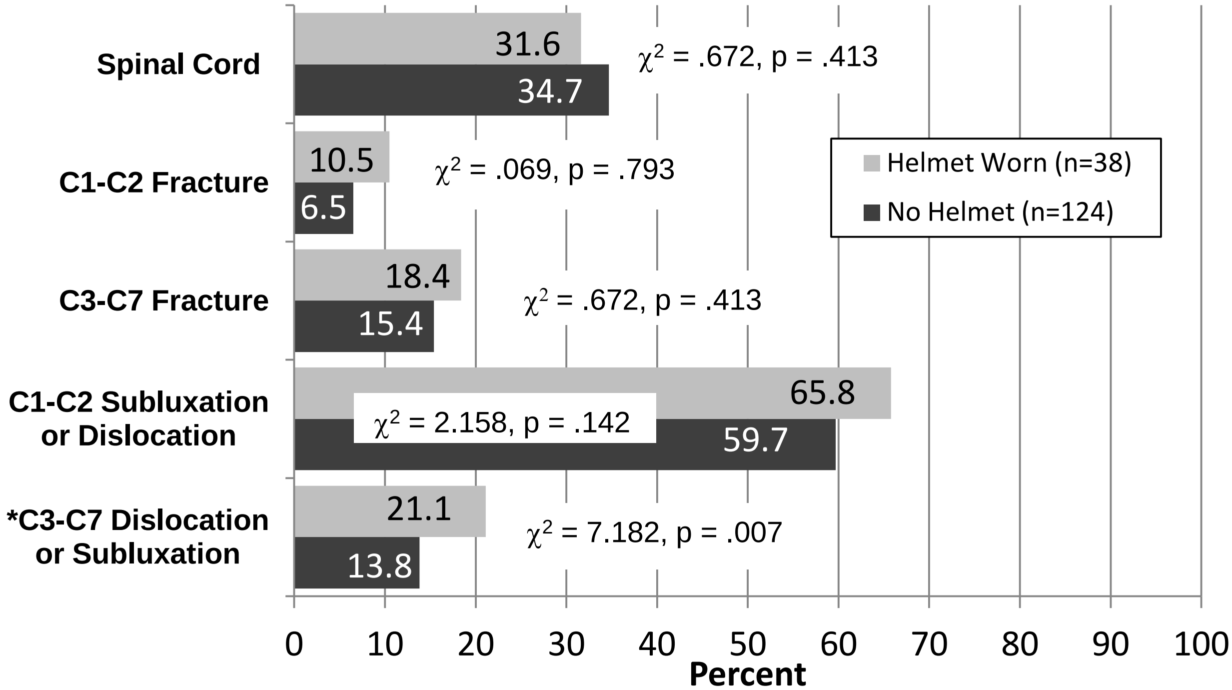


Figure 5. Cervical soft tissue injury rates for helmeted and unhelmeted riders in high severity crashes.

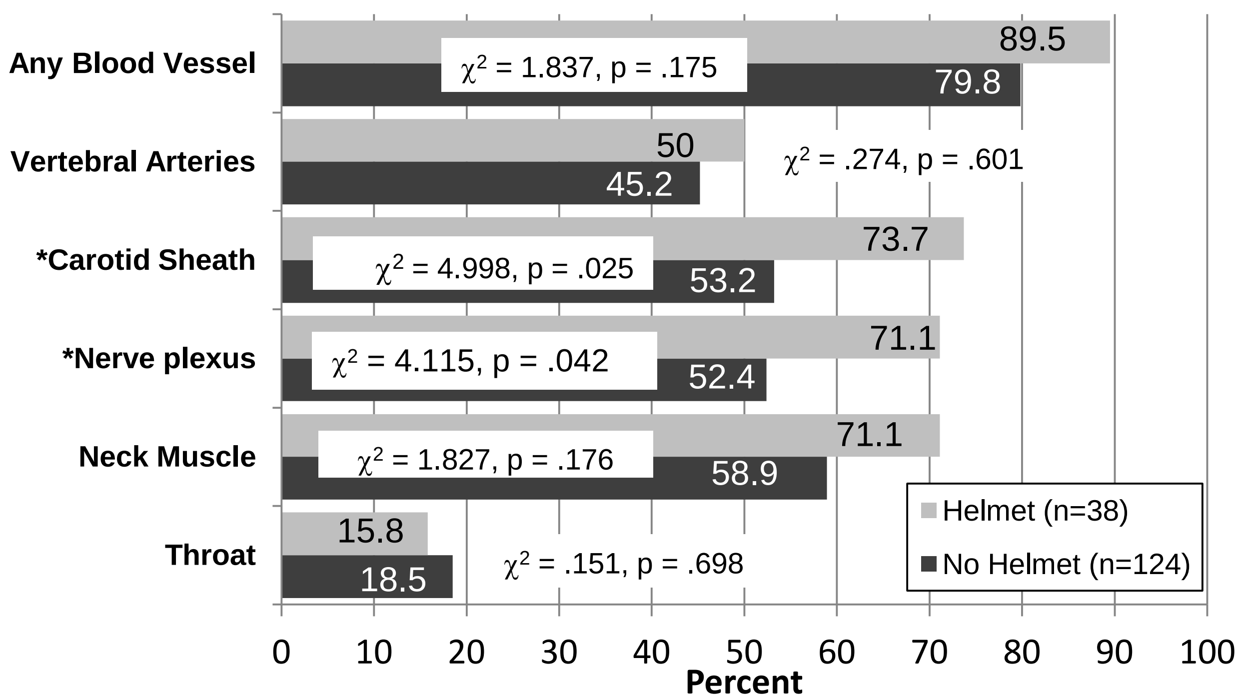


Figure 6. Spinal cord and spinal column injury rates for helmeted and unhelmeted riders in low-severity crashes

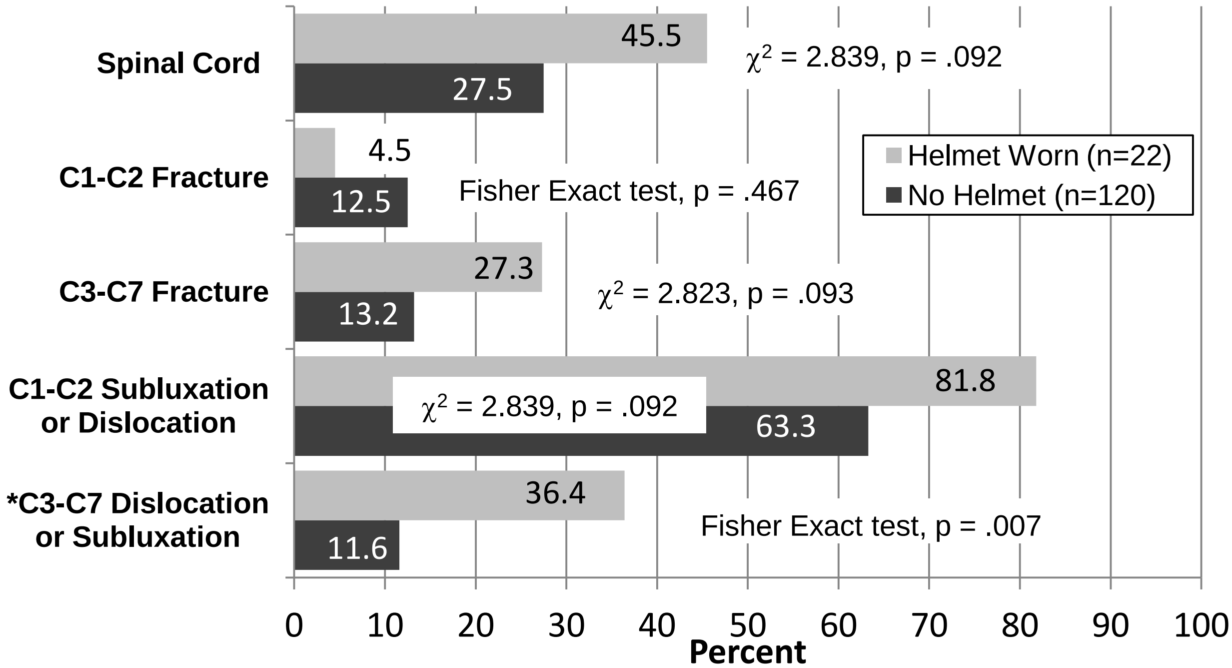


Figure 7. Cervical soft tissue injury rates for helmeted and unhelmeted riders in low-severity crashes

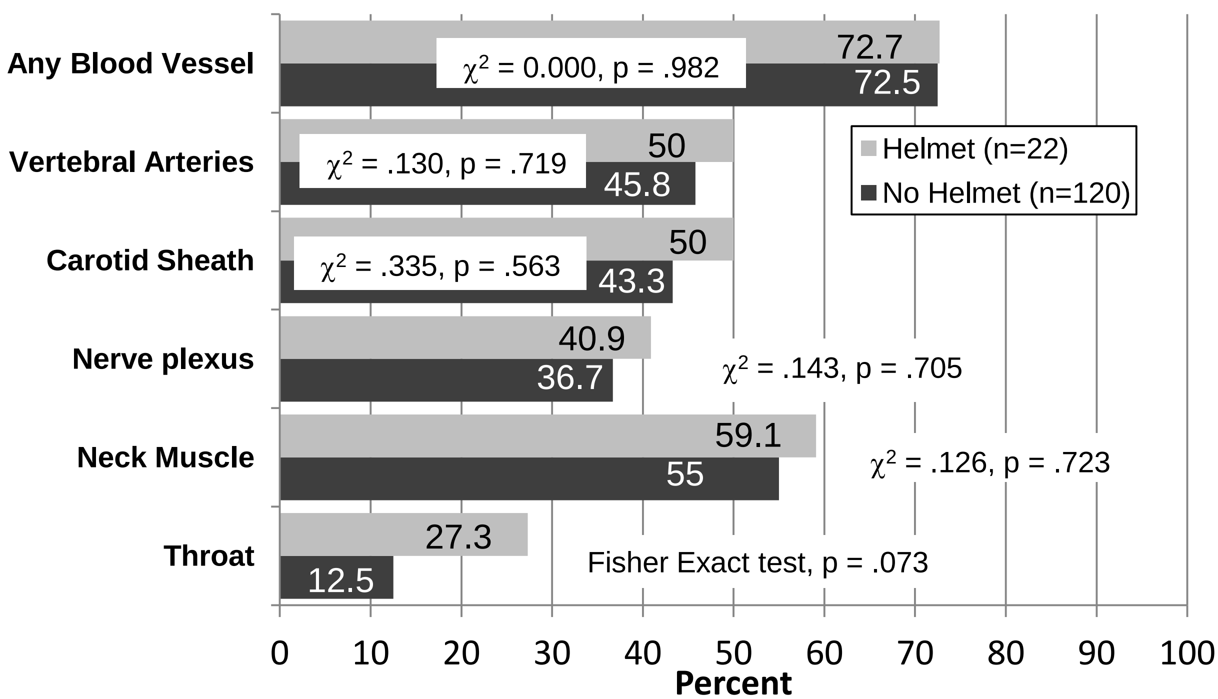


Figure 8. Spinal cord and spinal column injury rates among all 304 fatally injured riders

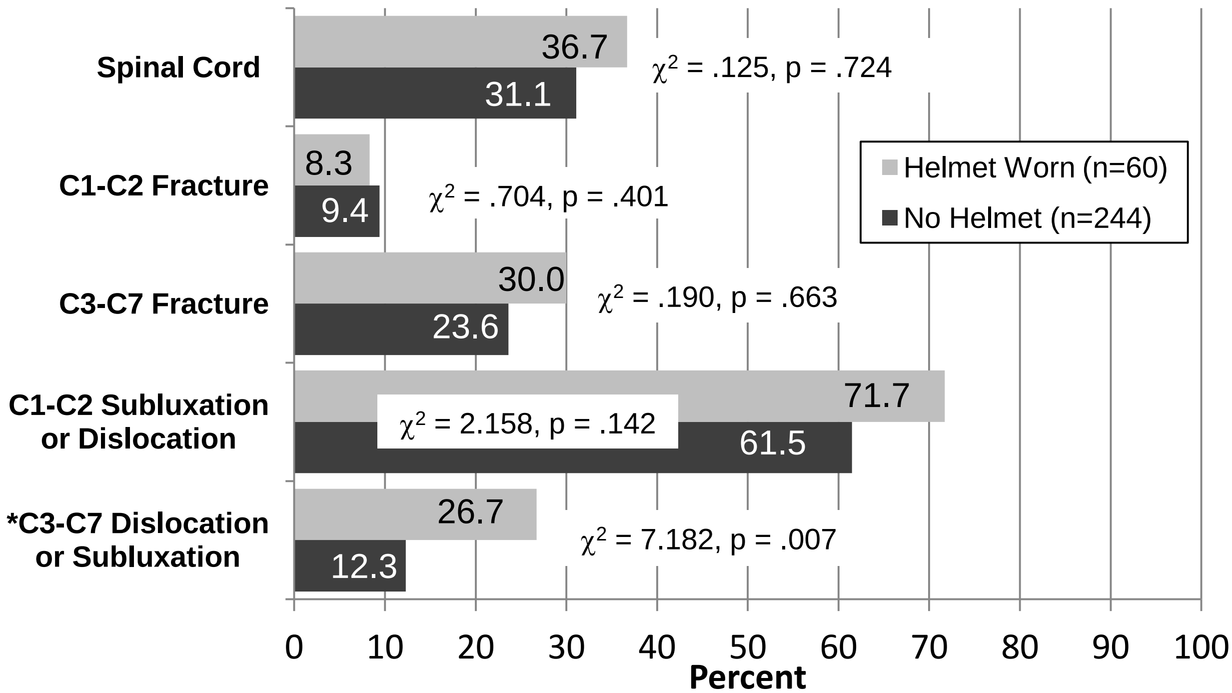
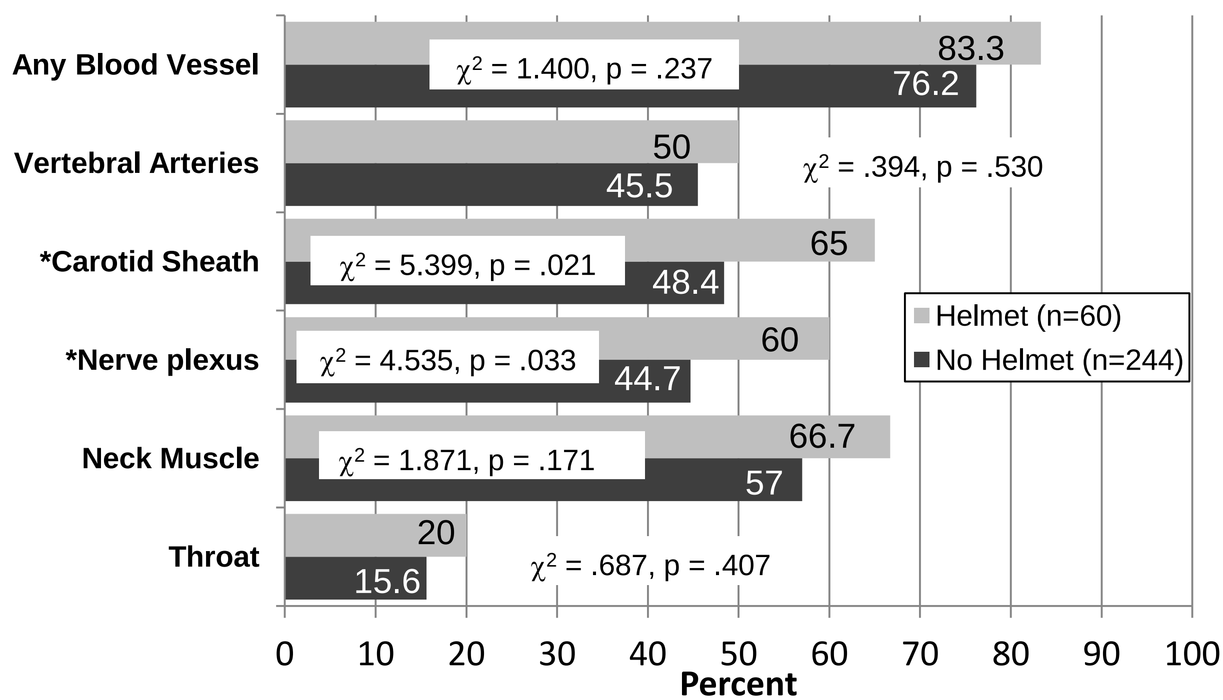


Figure 9. Soft tissue neck injury rates among all 304 fatally injured riders



All 304 fatal crashes

The neck injury rates for riders in low severity crashes are shown in Figure 8 (spinal cord and cervical spine) and Figure 9 (cervical soft tissues). Among all 304 fatally injured riders in this study, three injuries occurred significantly more often among helmeted riders: subluxation or dislocation of the cervical spine in the C3-C7 region, hemorrhage in the carotid sheath and hemorrhage surrounding a nerve trunk or plexus. Helmeted rider C3-C7 dislocation/subluxation injuries were significantly more common in both low-severity and high-severity crashes, while hemorrhage in the carotid sheath or surrounding nerves plexes was significantly more common in high-severity crashes but not in the low-severity crashes.

Table 1. Summary of differences between helmet use and non-use on injuries

Injury	Helmet effect				
	Significant reduction	Non-significant reduction[a]	No effect	Non-significant increase[a]	Significant increase
Spinal cord			1, 2	3	
C1-C2 Fracture			1, 2, 3		
C3-C7 Fracture			1, 2	3	
C1-C2 Sublux/Disloc			1, 2	3	
C3-C7 Sublux/Disloc					1, 2, 3
Cervical blood vessel			1, 2, 3		
Vertebral artery			1, 2, 3		
Carotid sheath			3		1, 2
Hemorrhage on nerves			3		1, 2
Muscle			1, 2, 3		
Throat			1, 2	3	

1 All 304 riders (60 helmeted) 2. 162 riders in high-severity crashes (38 helmeted)
3. 142 riders riders in low-severity crashes (22 helmeted) a. Probability between .05 and .10

The effect of helmet use on the different injuries in these fatal accidents is summarized in Table 1. Three injuries showed a statistically significant increase: 1) C3-C7 dislocation and subluxation injuries; 2) Hemorrhage in the carotid sheath, and 3) hemorrhage surrounding nerve roots and trucks, the latter two particularly in the high severity crashes. Spinal cord injuries, throat injuries and C3-C7 fractures may be increased with helmet use in low severity crashes, yet hemorrhages in or around the carotid sheath and nerve trunks were decreased.

Helmet weight in all 304 fatalities

Helmet coverage or weight may affect the frequency of neck injuries. For example, helmets might reduce neck injuries by reducing impact loads transmitted from the head to the neck. On the other hand, one could argue that helmet use might increase neck injuries, possibly by direct contact (presumably some sort of “karate-chop” effect) or by the added mass of the helmet increasing the stresses acting on the neck, especially on soft tissues.

However, the frequency of spinal cord injury did not appear to vary in any consistent way with the weight of the helmet. If helmet weight adversely affects spinal cord injuries then one would expect them to increase as helmet weight increases. Figure 9 shows nothing resembling a consistent relationship between helmet weight and the frequency of spinal cord injuries. In fact, the highest rates of spinal cord injury were found in the middle weights around 2 ¼ to 3 pounds (1020 – 1360g), in which 14 of 28 riders sustained injury. Much lower rates were observed for heavier helmets – two of 13 cases (15%). By comparison, 76 of 244 unhelmeted riders (31%) had a spinal cord injury. Perhaps this data set has too few cases for any consistent trend to emerge. Nonetheless, the data available here fail to suggest any simple relationship between increasing helmet weight and increasing spinal cord injury rates.

Similar evidence appears for injuries to the vertebrae and joints of the neck. Cervical spine fractures occurred in three of 19 riders (16%) wearing a helmet that weighed 2¾ pounds or more (>1250g) compared to 11 of 31 of riders (36%) with a helmet under 2¾ lbs. and 55 of 244 unhelmeted riders (23%). C1-C2 subluxation / dislocation injuries were extremely common, occurring among 61.5% of unhelmeted riders, 77% of 31 riders with a helmet weighing less than 1250g and 68% of riders with a helmet over 1250g. C3-C7 subluxation / dislocation injuries were identified in 13% of unhelmeted riders, 26% of those with a helmet under 1250g and 21% of those with a helmet over 1250g. That is, cervical spine injuries tended to be slightly higher among riders wearing helmets weighing less that 2¾ pounds than for riders wearing a heavier helmet or no helmet at all so that the role of helmet weight in spinal cord and cervical spine injuries is muddled, at best.

Figure 10 fails to show any obvious trend of more frequent vascular injuries generally as helmet weight goes up, nor is any trend apparent for vertebral artery injuries. However there may be a trend linking helmet weight to the frequency of hemorrhage in the carotid sheath and hemorrhage surrounding nerve trunks and plexes. Carotid sheath hemorrhage was reported for 48% of unhelmeted riders, 58% of riders with a helmet under 1250g and 84% of riders wearing a helmet that weighed over 1250g. The trend is less pronounced for hemorrhages surrounding nerve plexes and trunks: 45% of unhelmeted riders, 55% of riders with a helmet under 1250g and 68% of riders wearing a helmet weighing over 1250g.

Figure 9. Frequency of spinal cord and spinal column injuries as a function of helmet weight

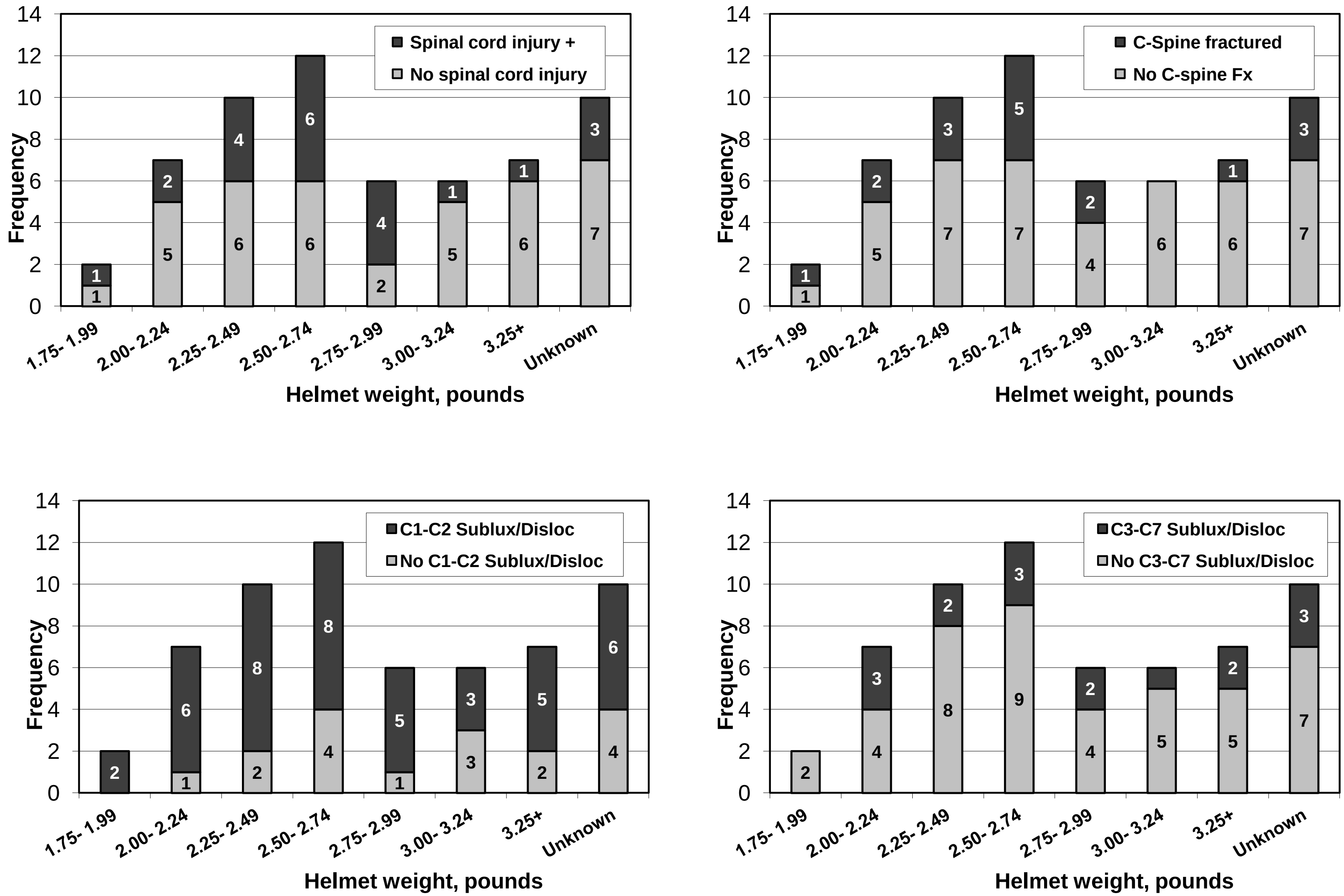
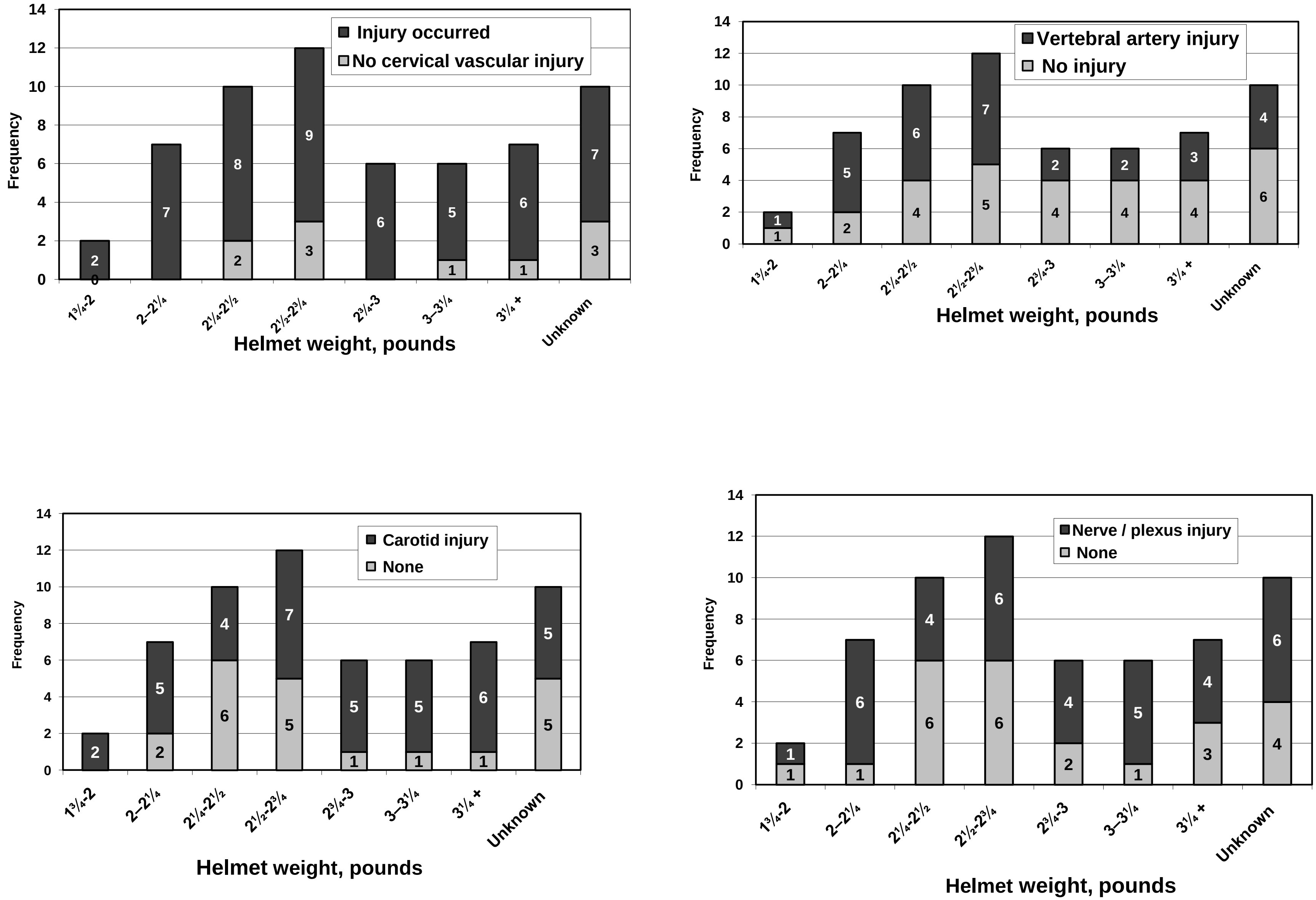


Figure 10. Frequency of cervical soft tissue injuries as a function of helmet weight



DISCUSSION

With a couple exceptions, helmet use had no significant effect on neck injuries in these fatal motorcycle crashes. Helmeted riders often had slightly more injuries than unhelmeted riders, but the differences were usually not statistically significant. Helmeted riders were not at greater risk for spinal cord injuries, cervical spine fractures or C1-C2 subluxation / dislocation injuries. Soft tissue injuries in the neck – injury to the vertebral arteries, hemorrhage surrounding nerves such as the phrenic nerve or brachial plexus, throat injuries – were mostly unaffected by helmet use. Helmet weight did not have a consistent effect on most of the injuries examined here.

One exception to this general pattern was an increase in hemorrhage within the carotid sheath, which carries the internal carotid artery and the vagus nerve. Adverse consequences of carotid hemorrhage in survivors appear to be rare but may be associated with later complications of thrombosis or aneurysm. The vagus nerve affects a variety of functions including heart rate, sweating, peristalsis and even a few muscles in the throat and these could be affected by hemorrhage that compresses the vagus. Kasantikul et al. (2003) also frequent carotid sheath hemorrhage in a sample of 73 fatally injured motorcyclists in Thailand but failed to find an increased risk of the injury among helmeted riders.

A complex relationship emerges for C3-C7 subluxation / dislocation injuries and spinal cord injuries in the same region. That is, even though helmets increase the risk of C3-C7 subluxation-dislocation, which in turn increases the risk of C3-C7 spinal cord injury, helmet use failed to increase the risk of C3-C7 spinal cord injury. The 60 helmeted riders were 20% of the 304 cases reported here and 18% of the 17 C3-C7 spinal cord injuries. C3-C7 subluxation – dislocation injuries have a significantly higher rate of spinal cord injuries in that same region (3% vs. 19%; Fisher Exact test $p < .001$). However, helmet use was associated with a non-significantly lower risk of C3-C7 spinal cord injury whether C3-C7 subluxation-dislocation occurred (7 of 31 vs. 2 of 16; Fisher Exact test, $p = .697$) or did not occur (7 of 213 vs. 1 of 44; Fisher Exact test, $p = 1.0$).

This is not the first study to find little relationship between helmet use and neck injuries. In fact, a recent review by the Cochrane Collaboration (Liu et al., 2009) summarized the results of 16 studies. Only one of 16 studies they analyzed (Sarkar et al., 1995) reported a significant reduction in neck injury risk for helmet users; the others reported no significant differences. Since then, Crompton et al. (2011) analyzed injury data from 40,588 motorcyclists in the National Trauma Databank and reported a neck injury among 4.4% of unhelmeted riders compared to 3.5% of those who wore a helmet – a 20% reduction in neck injury risk for helmeted riders.

In summary, the data reported in this study suggest a high incidence of neck injuries in fatal motorcycle crashes. Only 18 riders of 304 these fatally injured riders (6%) had no neck injury. Overwhelmingly these neck injuries were not from direct contact but rather were indirect injuries resulting from stress and hypermotion of the neck during the crash sequence. Helmets appear to be associated with a non-significant increase in all but a few injuries. Those exceptions where the increased risk of injury were statistically significant or bordering on significance are 1) C3-C7 subluxation-dislocation (but not C3-C7 spinal cord injuries); 2) hemorrhage in the carotid sheath; and 3) hemorrhage surrounding nerve trunks and plexes. It is unlikely any of these three injury groups are life-threatening in themselves. On the other hand, the effectiveness of helmet use in preventing death and severe brain injury has been demonstrated over and over (e.g., Liu et al., 2009; Crompton et al., 2011). As just one example, Ouellet et al., reported that about half of fatally injured riders would die of their injuries outside the head/neck region. Of the half whose below-the-neck injuries are likely survivable, helmet use could prevent about 80% of deaths. This estimated reduction is the risk of death (80% of half, or 40% of the total) corresponds closely to Deutermann's (2004) estimate that helmet use reduces the risk of dying in a motorcycle crash by 37%.

ACKNOWLEDGEMENTS

The late Hugh H. Hurt, Jr. was Principal Investigator on the Motorcycle Accident Research Project at the University of Southern California when this research took place (1978-80). Before his death he contributed as an author to this paper as well as earlier versions (e.g. Hurt et al., 1986).

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