Head Injury Mechanisms in Helmet-Protected Motorcyclists: Prospective Multicenter Study

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Background: In a prospective study, three research groups at Hannover (H) and Munich (M) in Germany and Glasgow (G) in the United Kingdom collected data from motorcycle crashes between July 1996 and July 1998 to investigate head injury mechanisms in helmet-protected motorcyclists.

Methods: The head lesions of motorcyclists with Abbreviated Injury Score-Head (AIS_{Head}) 2+ injuries and/or helmet impact were classified into direct force effect (DFE) and indirect force effect (IFE) lesions. The effecting forces and the force consequences were analyzed in detail.

Results: Two-hundred twenty-six motorcyclists (H, n = 115; M, n = 56; and G, n = 55) were included. Collision opponents were cars (57.8%), trucks (8.0%), pedestrians (2.3%), bicycles (1.4%), two-wheel motor vehicles (0.8%), and others (4.2%). In 25.4% no other moving object was involved. The mean impact speed was 55 km/h (range, 0–120 km/h) and correlated with AIS_{Head}. Seventy-six (33%) motorcyclists had no head injury, 21% (n = 48) AIS_{Head} 1, and 46% (n = 103) AIS_{Head} 2+. Four hundred nine head lesions were further classified: 36.9% DFE and 63.1% IFE. Lesions included 20.5% bone, 51.3% brain, and 28.1% skin. The most frequent brain lesions were subdural hematomas (22.4%, n = 47) and subarachnoid hematomas (25.2%, n = 53). Lesions of skin or bone were mainly DFE lesions, whereas brain lesions were mostly IFE lesions.

Conclusion: A modification of the design of the helmet shell may have a preventative effect on DFE lesions, which are caused by a high amount of direct force transfer. Acceleration or deceleration forces induce IFE lesions, particularly rotation, which is an important and underestimated factor. The reduction of the effecting forces and the kinetic consequences should be a goal for future motorcycle helmet generations.

Key Words: Brain injury, Head injury, Injury mechanism, Motorcycle crash, Motorcycle helmet.

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As opposed to car crashes, motorcycle crashes have received relatively minor attention by the research community. Concerning vehicular trauma in motorcyclists, the gross majority of articles mainly mention the injury-preventing effect of the helmet.[1–21] These results confirm the unique effectiveness of comprehensive helmet-use laws in applying the proven public health benefits of helmet use to the reduction of motorcycle injuries and deaths. At present, a standard for testing helmets under defined conditions was created by the Economic Commission for Europe (ECE)[22] to ensure that the helmets that are currently offered on the market are able to protect the motorcyclist. Despite these efforts, a high percentage and duration of hospitalization is observed even in helmet-protected motorcyclists.[23,24] In many cases, there remains a high degree of impairment in the long-term outcome.[25] Especially in the case of a patient with multiple injuries, the long-term outcome is considerably influenced by the severity of the head injury.[26]

The aim of the present study was to analyze the current situation of a protection standard in helmet construction in Europe and to evaluate the mechanism of head and brain injuries in helmet-protected motorcyclists to create a basis for further development of prophylactic devices.

MATERIALS AND METHODS

In a prospective study, three research groups at Hannover and Munich in Germany and Glasgow in the United Kingdom collected data from motorcycle crashes during the period July 1996 to July 1998. The data were obtained at the accident scene, the initial treating medical institution and, in case of fatalities, at the institution performing the autopsy. In addition to the standard local process (see below) within the European Cooperation in the Field of Scientific and Technical Research (COST 327) project of the European Commission, a specific database was developed, and standardized forms were used for data collection in all centers.[27]

This procedure was limited to cases fulfilling the following criteria: occupants of two-wheel motor vehicles (TWMVs); integral or jet-type helmet fitting the ECE R.22 standard being worn;[22] and head/neck injuries of Abbreviated Injury Scale (AIS) score of 2 or above, or known head/helmet contact with AIS head/neck score lower than 2.[28] The forms

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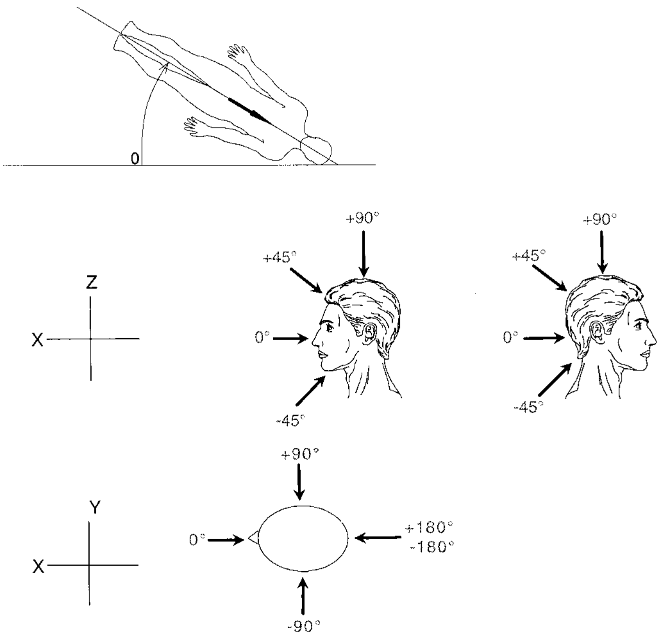

Fig. 1. *Body and head impact angle classification.*

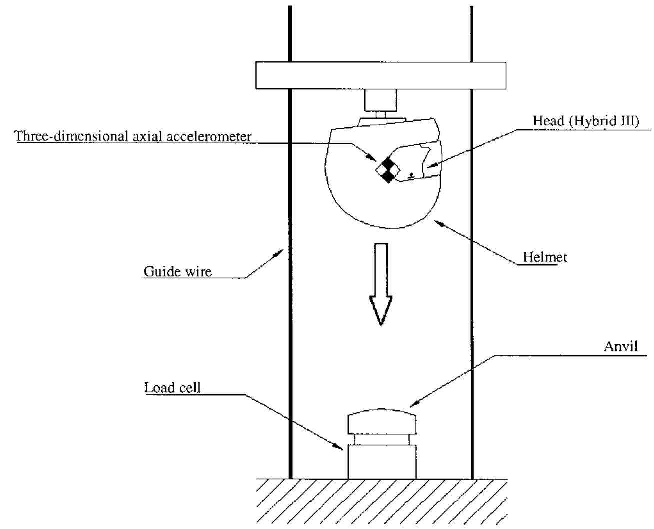

Fig. 3. *ECE R.22–04 standard testing setup (fall height, 2.87 m; maximum acceleration, 275*g*; impact duration, 150 g/5 ms; anvil form, even or rounded). Four different helmet regions are tested (B, front; X, left/right lateral; R, rear; P, crown). In the figure above, a test for region P is shown.*[22]

contain anthropometric data; medical data such as injury type (i.e., fractures, abrasion, intracerebral hematomas, etc.) and injury severity (AIS); and technical data such as seating position, type of collision, vehicle impact speed, head impact speed, head and body impact angle (Fig. 1), helmet weight, and type and location of helmet damage (Fig. 2).

The helmet damage mechanism was taken into consideration to the current ECE test line (Fig. 3). The vehicle impact speed is the speed of the vehicle (motorcycle) at the beginning of the crash. The vehicle impact speed was evaluated with a mathematical impact analysis using the basic principles of physics. Traces of the movement of the vehicles, the vehicle deformation patterns, and the statements of the people involved concerning the driving behavior before the collision were taken into consideration. On the basis of the calculated speed of the motorcycle, the head impact speed was evaluated with an analysis of body kinematics during the following phase, and the position of the body at the point of impact against the road surface, vehicle parts, or other obstacles. For further evaluation, the highest head impact speed during the entire crash was considered, which in 50% of cases was not the first impact. The helmet damage was assessed by the engineers of the study group. By analyzing the amount of dust or dirt on scratches or breaks, the time of the damage could be estimated.

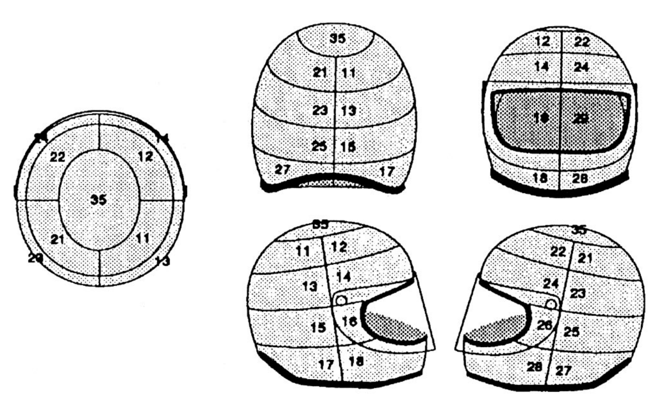

Fig. 2. *Helmet segments for classification of head lesion location.*

Identical methodologies regarding the accident, vehicle impact, and helmet data were used at the three centers. The technical data were gathered directly at the accident scenes at all three centers in all cases. This investigation was performed in Hannover directly after the accident, and in Glasgow and Munich at a later stage. Technical parameters were measured and recorded at the scene. Photographs were taken at the scenes and were directly used for further accident reconstruction. All vehicles were technically investigated.

The head injuries AIS 2+ were further analyzed. The single lesions of the head region were classified into lesions caused by direct force effect (DFE) or indirect force effect (IFE). All coup lesions that were directly caused by a force effecting the damaged structures were defined as DFE (e.g., skin laceration, impression fractures, brain lesion beneath impression fractures). Consequently, a DFE of deeper structures such as damage to the brain was only assumed when all of the more superficial structures in the same area were also damaged. IFE lesions were all contrecoup lesions and all coup lesion indirectly caused by the effecting force (i.e., when forces were transmitted through more superficial structures in the same area without damaging them).

The direction of the force was classified as well as force effects such as rotation and hyperextension on the basis of the virtually reconstructed movement of the body during the impact phase. All the data forms were sent to Hannover, and further coding was performed by the Accident Research Unit in Hannover. Under this procedure, the interrater bias was avoided. This analysis was performed by engineers under responsibility of one of the technical authors (D.O.). Independently, two trauma surgeons (M.R. and U.L.) analyzed computed tomographic (CT) scans and/or autopsy reports/ pictures for lesion type/location and the determination of the kinetic consequence of the effecting force. Each case with any deviation in any classification (n = 10) was discussed and reclassified by both investigative teams. For statistical analysis, a t, χ^2, Pearson, or linear trend test was used.

Individual Local Processing Features

Hannover, Germany

The accident files had been prepared by scientific teams of the Accident Research Unit. The teams had been informed directly via police radio and arrived at the accident scenes within 10 minutes in their own vehicles. In the area of the rural district and the town of Hannover, Germany (1.2 million inhabitants), approximately 6,000 vehicular collisions with consequent injuries to persons occur each year. Around 1,000 (17%) of these collisions have been documented annually since 1988. This was performed according to a statistical sample design plan. In the years 1973 to 1987, an average of 300 vehicular collisions per year were evaluated. In addition to technical indications and an evaluation of the damage to the vehicle and helmet, the files also included medical details and degree of injuries to persons. Individuals who died before hospital admittance were not included.

The first medical facility providing care for the injured person documented the diagnosis and type of injury. Photographs of the vehicular collision scene and the vehicles as well as other relevant radiographs were collected by the staff of the Accident Research Unit.

Glasgow, United Kingdom

A Motorcycle Accident Study at the Southern General Hospital started in 1984 involving collaboration with the Department of Neuropathology, the Department of Transport Vehicle Inspectors, Strathclyde Police, and the Crown Office (Scotland). The police forward all reports of accidents involving motorcycles in the Strathclyde region (2.3 million inhabitants) to the Department of Neuropathology. The department then investigates any accident involving rider or pillion passenger who sustained a head injury and/or other injury with AIS 2+, or who spent 24 hours or more as an inpatient. Accident and vehicle data forms were completed by the Department of Transport's vehicle inspectors containing technical data derived from an investigation of the vehicles, accident scenes, helmets, clothing, and photographs. The Department of Neuropathology obtained injury data forms derived from medical records and postmortem reports including brain injury diagrams from neuroradiology and brain examination in fatal cases.[29]

Munich, Germany

The assignment of the Institute for Forensic Medicine gathered data including biomechanical analysis and assessment of forensic traffic accident cases commonly derived from autopsy data, police reports, and technical expert investigations. The investigation area includes the town and the rural district of Munich (3 million inhabitants). From more than 2,000 autopsy cases currently investigated per year, approximately one third represent a variety of fatal traffic accidents, with a considerable percentage of motorcycle crashes. Additionally, a number of nonfatal motorcycle cases are the subject of investigation using the medical records. The selection of the cases is mainly determined by criminal or liability relevance, for example, to detect an unknown driver, safety-belt and helmet usage, etc. Generally, police and/or public prosecutors decide whether or not forensic investigation has to be performed. Furthermore, insurance companies frequently request analysis for liability cases. The technical reconstruction of the accident mechanisms was performed on the basis of the police protocols, including photographs of the accident scenes and vehicles.

RESULTS

Demographics

Between July 1996 and July 1998, 218 accidents were included from the different investigators in Germany and the United Kingdom for the purpose of the COST 327 project (Hannover [H], n = 111; Munich [M], n = 55; and Glasgow [G], n = 52). Two hundred nineteen TWMVs were examined, and medical and personal data were collected in 226 injured motorcyclists (H, n = 115; M, n = 56; G, n = 55) incurring 1,976 injuries. Drivers were 96.9% (n = 219) among those injured and 3.1% (n = 7) were passengers. Male subjects constituted 88.5% (n = 200); female subjects, 11.5% (n = 26). The mean age at the time of the accident was 28.9 years (range, 6–82 years). Passengers (mean age, 15.7 years [range, 6–51 years]) were younger than drivers (mean age, 30.1 years [range, 18–82 years]). Twenty-seven percent (n = 52) of motorcyclists were younger than 26, and 19.5% (n = 44) were older than 40 years at the time of the accident. Between Hannover, Munich, and Glasgow, no differences were found in the age distribution.

Injury Type and Severity

Thirty-three percent (n = 76) were included in the study because of helmet impact, but did not suffer a head injury. Twenty-one percent (n = 48) of the head injuries were classified AIS-Head (AIS_{Head}) 1 and 46% (n = 103) AIS_{Head} 2 or higher (AIS_{Head} 2+). Neck injuries were absent in 72.8% (n = 163), with 10.7% (n = 24) classified as AIS-Neck (AIS_{Neck}) 1, and 16.5% (n = 37) as AIS_{Neck} 2+ (Fig. 4). AIS_{Head} and AIS_{Neck} showed a positive correlation (r =

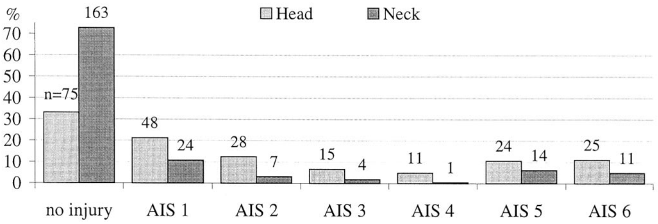

Fig. 4. *AIS_{Haed} and AIS_{Neck} in 226 motorcyclists (AIS_{Neck} unknown in two cases).*

0.523, $p = 0.05$), although 36% (59 of 163) of the individuals without neck injury were classified AIS_{Head} 2+. The fatality rates were as follows: H, 10% (n = 12); G, 35% (n = 19); and M, 95% (n = 53). The head injury was considered as the cause of death in 88% (n = 74): H, 83% (n = 10); G, 79% (n = 15); and M, 92% (n = 49).

Eighty-one (78.7%) motorcyclists with AIS_{Head} 2+ were analyzed regarding location and type of lesion involving the head region (H, n = 10; G, n = 24; and M, n = 47). With a total of 409 lesions, 36.9% (n = 151) were DFE and 63.1% (n = 258) IFE (Table 1). Bone lesions constituted 20.5% (n = 84), brain lesions 51.3% (n = 210), and skin lesions 28.1% (n = 115). IFE at the opposite side of the impact was observed in 16.4% of the cases and associated with DFE in all but one case.

Injury Mechanism

Collision Opponent

The collision opponents could be evaluated in 213 (97.3%) of the involved 219 TWMVs. Among those, 46.9% (n = 100) had two and 3.3% (n = 7) had three impacts. Overall, 57.8% (n = 123) of the TWMVs collided with cars, 8.0% (n = 17) with trucks, 2.3% (n = 5) with pedestrians, 1.4% (n = 3) with bicycles, 0.8% (n = 2) with other TW-MVs, and 4.2% (n = 9) with other moving objects. In 25.4% (n = 54), no other moving object was involved in any

Table 1 **Location and Type of 409 Lesions of the Head Region in 81 Motorcyclists AIS_{Head} 2+**

Type of Lesion	Force Effect				
	DFE		IFE		Total
	No.	%	No.	%	
Bone (n = 84)					
Total	**43**	**51.2**	**41**	**48.8**	**84**
Calotte	16	84.2	3	15.8	**19**
Base	0	0	33	100	**33**
Frontal sinus	2	100	0	0	**2**
Le Fort	6	100	0	0	**6**
Orbita	4	100	0	0	**4**
Nasal	4	100	0	0	**4**
Maxilla	5	100	0	0	**5**
Mandible	5	83.3	1	16.7	**6**
Dental	1	100	0	0	**1**
Dislocation/Fx upper cervical spine	0	0	4	100	**4**
Brain (n = 210)					
Total	**8**	**3.8**	**202**	**96.2**	**210**
EDH	0	0	7	100	**7**
SDH	1	2.1	46	97.9	**47**
SAH	0	0	53	100	**53**
Intracerebral hematoma	2	13.3	13	86.7	**15**
Ventricle bleeding	0	0	2	100	**2**
Artery rupture	0	0	1	100	**1**
Concussion	1	3.3	29	96.7	**30**
Contusion	1	11.1	8	88.9	**9**
Laceration	0	0	2	100	**2**
Compression	1	50	1	50	**2**
Swelling	0	0	8	100	**8**
Rupture, brain	1	6.7	14	93.3	**15**
Rupture, septum lucidum	0	0	4	100	**4**
Brain stem	1	6.7	14	93.3	**15**
Skin (n = 115)					
Total	**100**	**87.0**	**15**	**13.0**	**115**
Hematoma	35	87.5	5	12.5	**40**
Wound	10	83.3	2	16.7	**12**
Contusion	15	75	5	25	**20**
Laceration	21	91.3	2	8.7	**23**
Abrasion	19	95	1	5	**20**
Total	151	36.9	258	63.1	**409**

Table 2 **Direction of the First Impact in 219 TWMVs**

First Collision	H		M		G	
	No.	%	No.	%	No.	%
Fall before	5	4.5	12	21.8	3	5.6
1 o'clock	11	9.9	4	7.3	2	3.8
2 o'clock	7	6.3	1	1.8	2	3.8
3 o'clock	15	13.5	9	16.4	6	11.4
4 o'clock	—	—	1	1.8	—	—
5 o'clock	1	0.9	—	—	—	—
6 o'clock	7	6.3	2	3.6	3	5.6
7 o'clock	3	2.7	—	—	—	—
8 o'clock	—	—	—	—	—	—
9 o'clock	8	7.2	1	1.8	3	5.6
10 o'clock	4	3.6	1	1.8	1	1.9
11 o'clock	11	9.9	3	5.5	—	—
12 o'clock	38	34.3	21	38.2	30	56.7
Unknown	1	0.9	—	—	3	5.6
Total	111	50.7	55	25.1	53	24.2

TWMUs, two-wheel motor vehicles; H, Hannover; M, Munich; G, Glasgow.

collision. Sixty-two percent (n = 135) of the collision opponents during the first impact were vehicles, whereas 65% (n = 65) of the second impacts and 71.4% (n = 5) of the third impacts involved the road surface. Between Hannover, Glasgow, and Munich, no differences in the collision opponent distribution were observed.

Direction of Vehicle Impact

The direction of the vehicle impacts were classified clockwise into 12 different zones: 40.6% (n = 89) of the first impacts were "12 o'clock" impacts (i.e., impacts directed from the front toward the rear of the TWMV). The highest percentage of 12 o'clock impacts was observed in Munich (56.7%), followed by Glasgow (38.2%) and Hannover (34.2%) (Table 2). The type of collision was classified into seven groups[30] and correlated with the AIS_{Head} in 113 (51.6%) of the TWMVs (Table 3). Type 7 collisions were observed in 38.9% (n = 44) (collisions against pedestrians, bicycles, and nonmoving objects) and type 4 collisions were observed in 31.0% (n = 35) (oblique against the side of a four-wheel vehicle). The highest AIS_{Head} was observed in type 2 (head-on against a four-wheel vehicle).

Vehicle Impact Speed and Head Impact Speed

The impact speed (IS) of the first collision could be determined in 181 (82.6%) of TWMVs (Fig. 5). The mean IS was 55 km/h (range, 0–120 km/h) (mean IS: H, 49.4 km/h; G, 54.9 km/h; and M, 73.7 km/h). The head impact speed (HIS) could be determined in 153 (67.7%) of motorcyclists and in 72 (69.9%) of motorcyclists with AIS_{Head} 2+ (Fig. 6). A HIS of $\leq$ 30 km/h was determined in 55.6% (n = 45) of motorcyclists with $AIS_{Head} < 2$ (n = 81) and in 16.7% (n = 12) of motorcyclists with AIS_{Head} 2+ (Table 4). The AIS_{Head} correlated with the HIS ($r = 0.398$, $p = 0.02$).

Helmet Type, Effectiveness, and Damage

The helmet type was classified in 205 (90.7%) of motorcyclists. Eighty-nine percent (n = 182) were full-face helmets, and 12.3% (n = 23) were open-face helmets. Fifteen percent (n = 16) of motorcyclists evaluated in Hannover wore open-face helmets, compared with 7.1% (n = 4) in Munich and 3.6% (n = 2) in Glasgow.

Whether or not a helmet was worn during the accident could be determined in 198 (87.7%) of motorcyclists. Loss of the helmet occurred in 11.1% (n = 22) (full-face, n = 17

Table 3 **Collision Type and AIS_{Head} in 113 TWMVs**

Collision Types	Description	% of Total	Maximum AIS_{Head} of Motorcyclists			
			Uninjured (%)	AIS_{head} 1 (%)	AIS_{head} 2–4 (%)	AIS_{head} 5/6 (%)
Type 1	Side collision against the front of a four-wheel vehicle	1.8	100.0	—	—	—
Type 2	Head-on collision against the front of a four-wheel vehicle	8.8	—	10.0	20.0	70.0
Type 3	Head-on against the side of a four-wheel vehicle	14.2	62.5	6.2	18.8	12.5
Type 4	Oblique collision against the side of a four-wheel vehicle	31.0	54.3	20.0	20.0	5.7
Type 5	Head-on collision against the rear-end of a four-wheel vehicle	5.3	50.0	50.0	—	—
Type 6	Rear-end collision against the front of a four-wheel vehicle	—	—	—	—	—
Type 7	Collision against pedestrians, bicycles, nonmoving objects	38.9	20.5	29.5	31.8	18.2

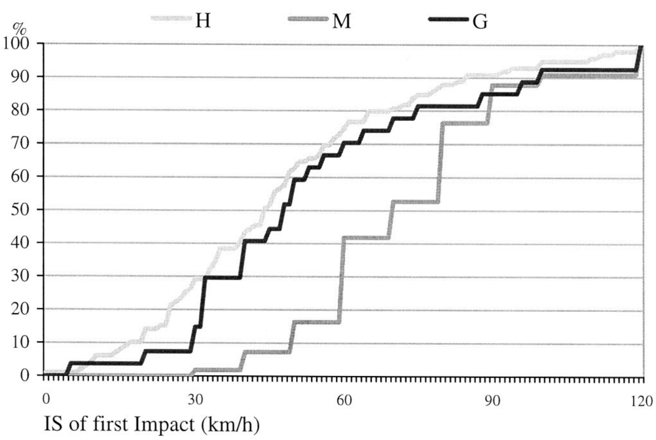

Fig. 5. *Vehicle impact speed (IS) of the first impact in 181 of 219 TWMVs.*

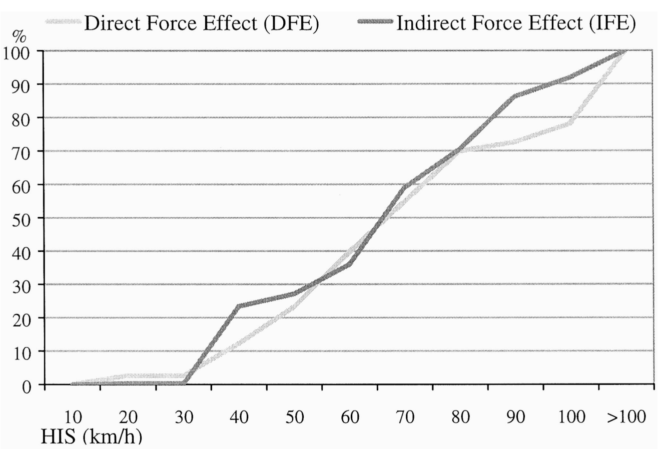

Fig. 6. *Head impact speed (HIS) of DFE and IFE.*

[9.3%]; jet type, n = 5 [22%]) of those motorcyclist victims, in one case before the first impact, in 14 cases after the first impact, and in four cases after the second impact (not further specified, n = 3). In 50% (n = 11) of the lost helmets, the chin strap was intact and closed. The strap was torn out of the fixation in 9% (n = 2) or torn itself in 14% (n = 3). In six (27%) lost helmets the strap was open; further investigation showed that the strap was pulled through the fixation during the accident in three (14%) cases. In the remaining three (14%) cases, the strap was considered to be not closed at the time of the accident. Among the nonlost helmets (n = 176 [89%]), 95% (n = 167) of the straps were closed at the prior evaluation, 5% (n = 9) were open, and no strap was torn. The distribution of the strap condition differed significantly between cases with lost or nonlost helmet (linear trend test, $p = 0.01$). AIS_{Head} and fatality rate were higher when the helmet was lost during the accident (lost helmet [n = 22]: AIS_{Head} 4.2 [range, 1–6], 68% [n = 15] fatalities; nonlost helmet [n = 176]: AIS_{Head} 2.5 [range, 0–6], 38% [n = 69] fatalities; difference AIS_{Head}, *t* test, $p = 0.05$; fatality rate, χ^2 test, $p =$ 0,01). The helmet weight was determined in 84 (37%) motorcyclists. The mean helmet weight amounted to 1,125 g (range, 780–1,620 g). In those cases, a negative correlation between AIS_{Neck} and helmet weight was observed ($r = -0.293$, $p = 0.01$).

Location and type of helmet damage were classified in 205 (90.7%) of motorcyclists. Helmet damage from the accident was differentiated to any previous damage to the helmet. Seven hundred twenty-eight single helmet lesions from the accident were observed. The helmet lesions were located in lateral right (lateral in sections 11–18) in 27.3% (n = 199), lateral left (lateral in sections 21–28) in 25.4% (n = 184), frontal (frontal in sections 12, 14, 18, 19, 22, 24, 28, and 29) in 26.9% (n = 196), and rear (rear in sections 11, 13, 15, 17, 21, 23, 25, and 27) in 21.6% (n = 157). Sixteen percent (n = 115) of helmet lesions were located at the chin guard (sections 18 and 28), and 5.8% (n = 42) at the visor (sections 19 and 29). Two lesions were observed at the crown region (section 35). The types of helmet lesion were most frequently scratches (n = 495 [68.0%]), followed by deformations (n = 136 [18.7%]), cracks (n = 91 [12.5%]), and others (n = 6

Table 4 AIS_{Head} and HIS of 153 Motorcyclists

HIS (km/h)	Total		No Injury		AIS 1		AIS 2		AIS 3		AIS 4		AIS 5		AIS 6	
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
≤10	11	7.2	8	72.7	2	18.2	—	—	—	—	—	—	1	9.1	—	—
11–20	15	9.8	2	13.3	10	66.7	3	20.0	—	—	—	—	—	—	—	—
21–30	31	20.2	14	45.1	9	29.0	3	9.7	—	—	—	—	2	6.5	3	9.7
31–40	14	9.2	3	21.4	4	28.7	3	21.4	—	—	1	7.1	2	14.3	1	7.1
41–50	24	15.7	8	33.3	4	16.7	5	20.8	1	4.2	—	—	2	8.3	4	16.7
51–60	22	14.4	5	22.7	2	9.1	5	22.7	—	—	4	18.2	1	4.6	5	22.7
61–70	11	7.2	2	18.2	3	27.3	1	9.1	—	—	—	—	1	9.1	4	36.3
71–80	11	7.2	—	—	—	—	1	9.1	—	—	1	9.1	7	63.6	2	18.2
81–90	4	2.6	1	25.0	—	—	—	—	—	—	1	25.0	1	25.0	1	25.0
91–100	6	3.9	3	50.0	—	—	—	—	—	—	—	—	1	16.7	2	33.3
>100	4	2.6	1	25.0	—	—	—	—	2	50.0	1	25.0	—	—	—	—
Total	153	100	47	30.7	34	22.2	21	13.7	3	2.0	8	5.2	18	11.8	22	14.4

HIS, head impact speed.

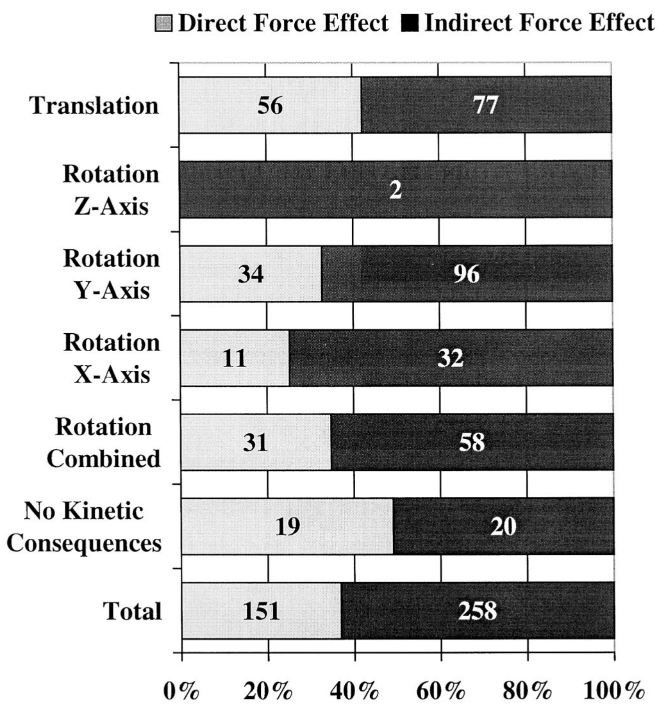

Fig. 7. *Kinetic consequences of the effecting forces in 409 lesions of the head region in 81 motorcyclists AIS_{Head} 2+.*

[0.8%]). Damage to the internal lining was found in 34 (17%) helmets. All these helmets also had a cracked shell. Vice versa, only 37% (34 of 91) of the helmets with cracked shells also showed damage to the internal lining.

Effecting Forces

Of forces resulting in head lesions (n = 409), 56.8% (n = 233) were directed from left to right (n = 108; head impact angle, XY = −90 ± 15 degrees) or right to left (n = 125; head impact angle, XY = 90 ± 15 degrees). In 27.3% (n = 112), the force direction was exactly front to occipital (n = 94; XY = 0 ± 15 degrees) or occipital to front (n = 18; XY = 180 ± 15 degrees). The forces were furthermore directed from front left (XY = −45 ± 15 degrees) in 15 and from front right (XY = 45 ± 15 degrees) in 12 cases toward the opposite side. Compression (n = 4) and axial load (n = 2; ZX = 90 ± 15 degrees) were rather seldom, as well as pure rotation (n = 3) and hyperextension (n = 3). The head impact angle correlated with the vehicle impact angle when the rider remained seated on the motorcycle at the time of the relevant head impact (head impact angle). In 75% of the cases, the rider fell from the motorcycle before the relevant head impact. In those cases, no correlation between vehicle impact angle and head impact angle was observed. The DFE lesions were mainly located in the area where the forces effected the head, and in IFE lesions, 20% of the cases were located on the opposite side. No relationship was found between damage to helmet internal lining regarding compression and other behavior and DFE. The kinetic consequence of the effecting force was an isolated translation in 32.6%; an isolated rotation around the X-, Y-, or Z-axis in 36.2%; and a combined rotation in 21.6%. In 9.6%, no kinetic consequence resulted (Fig. 7). DFE and IFE differed in the distribution of the kinetic force consequence (linear trend test, $p = 0.05$). DFE lesions were overrepresented when an isolated translation or no kinetic consequence occurred, and IFE lesions overbalanced in rotational motions.

Body Impact Angle

The body impact angle (BIA) was determined in 178 cases (78.6%) (G, n = 18; H, n = 108; and M, n = 52). Fifty-one percent (n = 90) of the BIAs amounted to 0 degrees and 11.8% (n = 21) to 90 degrees (Fig. 1). BIAs ≤ 10 degrees were determined as follows: G, 11.1% (n = 2); H, 58.3% (n = 63); and M, 48.1% (n = 25). In G, no 90-degree BIAs were observed; in H, 1.6% (n = 2); and in M, 35.2% (n = 19).

Helmet Impact in Comparison with the ECE R.22 Standard

Head impact speed and location of helmet lesion were used to compare the real helmet impact from our investigation with the impact of the ECE R.22–04 standard (Fig. 3), which was up-to-date at the time of the investigation (possible in 145 cases).[22] Forty percent of the real impacts were similar to that standard [11% at region B (front), 25% at region X (right/left side), 8% at region R (rear), 1% at region P (crown)]. When only comparing the amount of impact without consideration of the location, 90% (n = 131) of real impacts were below the test line (fatality rate, 31% [n = 41]). In the remaining cases (10% [n = 14]), a fatal outcome occurred without exception.

DISCUSSION

In motorcyclists, the "protecting effects" of special clothing, equipment and, especially, a helmet lower the collision impact for body and head.[12,17,31–34] At present, helmets that are available in Europe fulfill the ECE R.22 standard.[22] With this type of helmet protection, only 18.4% of all motorcyclist involved in crashes sustained head injuries, but 9.7% suffered from severe head injuries.[35] This corresponds to our observations in the department of trauma surgery of the Hannover Medical School, which is a Level I trauma center. Former studies have suggested that helmets may cause injury to parts of the head or neck because they add mass to the head.[36] However, intracranial cerebral injury; intracranial hemorrhage; and face, skull vault, and cervical spine injuries were more likely to be found in fatally injured unhelmeted motorcyclists than in helmeted motorcyclists. The protective value of helmets to reduce risk of facial injury is further mentioned.[6,10] Overall, the usage of helmets reduced the rate of head injuries, for example, in Germany from 40% to 18% in the recent decade.[30] These results expand on earlier reports showing that helmets provide protection for all types and locations of head injuries, and show that they are not associated with increased neck injury occurrence.[17] However, a helmet is only effective when it remains on the head during the accident. In our study, 11% of the helmets had been lost during the accident, more likely jet-type than full-face helmets. In 27% of those cases, the chin strap was not closed when the accident occurred; however, in 50% it was closed and in 24% it was torn or pulled out. Consequently, the fixation of the helmet has to be improved. The AIS_{Head} and fatality rate was higher when the helmet was lost during the accident. Only accidents with axial load shift and helmets weighing more than 1,500 g were found to increase the risk of a basal skull fracture. Therefore, high-weight helmets should be avoided.[36] The results of most studies underline the fact that motorcycle accidents are sustained by young men in their working prime; as a result, these accidents pose a tremendous burden to individuals and society, and every attempt should be made to offer highly qualified surgical and trauma care to minimize the damage to the motorcyclist.[37,38] Apart from the head injuries, injuries of the lower limbs are considered to cause a high degree of long-term impairment.[39,40] However, in most of the above-mentioned studies, the injury-preventing effect of the helmet was the main focus. Similar to passive car safety, a further analysis of the injury mechanism itself is important. Therefore, we performed an additional analysis of the injury mechanism on head injuries in light of technical indications. Of particular importance was the helmet destruction, pointing out the observation that the probability of brain injuries in the absence of evidence of an impact to the head is very low.[41]

To standardize the data registration, the same set of forms was used in all three research groups (COST 327). One of the weaknesses of our study is still the variation in the local processing features of data collection. In all three centers, the data were collected prospectively and derived from the same protocol. Individuals who died before hospital admittance were not included in Hannover, but were included in Munich and Glasgow. The technical data were gathered directly at the accident scenes at all three centers, in Hannover directly after the accident, and in Glasgow and Munich at a later stage. The vehicles were technically investigated in all cases. Because of the differences of the inclusion criteria, a comparison of data between the three centers may be biased. However, the intention of the study was not to compare three different cities, but to analyze a wide range and variety of motorcycle victims with head injuries to obtain an overview of the situation in Europe. The problem of reporter bias was minimized by taking photographs of the accident scenes, the involved vehicles, the clinical aspects of the injuries, the relevant radiographs and/or CT scans, and the relevant findings during autopsy. The technical classification was performed using a standardized protocol under the direction of the technical authors (D.O., D.D., and K.S.). All the data forms were then sent to Hannover and further coding (e.g., AIS, Injury Severity Score, DFE, IFE) was performed by the Accident Research Unit team. Under this procedure, the interrater bias was avoided. Misclassification of injury patterns was minimized by two trauma surgeons (M.R. and U.L.) performing the classifications independently. Each case with any deviation in one or more classifications was discussed and classified again by both together. With this prospective study design, objectivity, reliability, and validity for the evaluation could be provided. Considering the cost of additional information, a helmet damage assessment with CT scan as proposed by Cooter et al.[42] was not performed. Among the fatally injured, the highest percentage of 12 o'clock impacts and helmet loss during the accident correlated with the highest impact speed. In the study group, the highest AIS_{Head} was observed in head-on collision. AIS_{Head} and head impact speed correlated as well. We found no correlation of AIS_{Neck} and helmet weight in our study. In our classification into lesions caused by DFE or IFE, a high percentage of fractures as DFE and a high incidence of brain damage as IFE occurred. IFE at the opposite side of the impact were observed in 16.4% of the cases and were in all but one case associated with DFE. The further analysis of the injury mechanism showed that there has to be a high amount of direct force transfer through the helmet causing the DFE. The IFEs are caused by acceleration or deceleration forces of the entire head and helmet unit. Therefore, a modification of the design of the helmet may only have a preventing effect on the DFE. Although we found a relatively low number of skin lesions in comparison to the high number of brain lesions, an improved force distribution over the whole helmet surface by structural changes could further minimize the direct force transfer. Of particular note is that the area most likely to be violated was the chin guard and the area in the region of the visor attachment. This may indicate that the impacts to these areas were more severe or that these parts of the helmets are weaker than other areas. It is likely that the visor area is slightly weaker and that the impacts to the chin guard are particularly severe. Helmet standards should include tests that reflect these findings, particularly in relation to the chin guard as already included in Version 22–05 of ECE.[22] The temporal region was also vulnerable to injury and should be given more consideration in further revisions. The ECE R.22–04 standard, which was the current test line for the time of our investigation, did not consider the chin region. The impact of that test line is applied to the crown, lateral, front, and rear regions, where 40% of the real helmet impacts from our study occurred. When only considering the amount of impact and not the location, fatal outcome occurred without exception when the helmet impact was above the current test line. Thus, the actual test standard principally seems to be effective for potentially survivable impacts. However, a modification of the testing impact location with consideration of chin region is necessary.

To reduce the injury-causing acceleration or deceleration, a reduction of the impact forces to the helmet is essential. In cars, the cushioning of airbags reduce the impact and the acceleration/deceleration forces to head and torso considerably. Any kind of additional cushioning of the helmet should be a further technical effort. However, the effect on the head kinesis before, during, and after impact has to be considered in any kind of technical modification. The resulting kinetic consequences of the forces are frequently underestimated.[14] In our study, less than 10% of the head lesions occurred in an impact without kinetic consequences. Head lesions caused by indirect force effect were more prevalent in rotational kinetics. Presuming that rotation is an important mechanism inducing “indirect” head lesions, efforts should be made to minimize rotational consequences of the effecting forces. Remarkably, the effecting force itself was in less than 1% of the lesions (3 of 409) a pure rotation. However, the kinetic consequences were classified as rotation in almost 60% (isolated rotation around X-, Y-, or Z-axis, 36%; combined rotation, 22%). Consequently, effecting forces that were not a pure rotation do have rotational consequences in a high percentage, which must be caused by rotational components of the effecting force. Devices conjoining helmet and shoulders or torso may be conceivable to neutralize these rotational components and may prevent indirect head lesions. The design of these devices should also allow the motorcyclist to turn the head around 90 degrees to both sides to watch the rear traffic. A design that prevents fast rotations and that allows a slow turn of the head to watch the traffic should be developed.

In conclusion, the motorcycle helmets that are actually available provide a high preventive effect, especially in sufficiently reducing the direct force effect to the head. Further improvements of the helmet shell can further minimize the direct force effects. The lesions caused by indirect force effect (e.g., acceleration and deceleration) remain a problem. In particular, rotation is an important and underestimated factor. The reduction of the kinetic consequences of the effecting forces should be a direction for future motorcycle helmet generations.

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