IMPACT POINTS AND RESULTANT INJURIES TO THE HEAD OF MOTOR-CYCLISTS INVOLVED IN ACCIDENTS, WITH AND WITHOUT CRASH HELMETS

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INTRODUCTION

The great risk for motor-cyclists involved in traffic accidents is mainly based on the conception of the motor-cycle and the fact that the cyclist is not protected by either the passenger compartment or the safety belt. Apart from the extremities, the head is the most frequently injured body part.

Due to its anatomic structure the head is very susceptible to injuries. For a long time, the helmet was obviously attributed an important part in the prevention of skull injuries. Attempts to prevent damage to the skull by reduction, respectively dispersion of influental mechanical force are documented in the various helmet designs. It started with the early German buckle helmet, followed by the steel helmet for soldiers, the industrial and the miners' helmet, and the crash helmet for motor-cyclists. Leather-like headwear and helmets were already designed in the twenties for the motor-cyclist.

INJURY SITUATION

Of all external traffic participants, i.e. pedestrians, cyclists and motor-cyclists, the latter show the least risk to suffer head injuries. Almost all pedestrians involved in traffic accidents (87%), cyclists (85%), and motor-cyclists without crash helmets (70%) receive head injuries also. Of the helmet-wearing motor-cyclists (1) only 45% suffer head injuries. These facts clearly prove the protective quality of the crash helmet.

Basing on the 'Local Accident Documentations Hannover', a study of the Federal Highway Department Cologne, traffic accidents, involving 272 motor-cyclists were documented, reconstructed and analyzed. The results of this study, however, show that 10% of the helmet-protected motor-cyclists suffered fatal head injuries too. This fact justifies the question whether crash helmets in use today warrant an optimal head protection.

Depending on the accident condition (i.e. impact point on the accident partner, the collision angle, collision speeds), a different movement of the motor-cyclist during the collision and the runout phase can be established. A standardizing of similar kinematic patterns lead to the formation of collision types and kinematic- and runout categories (fig. 1). The most frequent impact object for the head is the road. 35.7% of the cyclists without helmets, and 59.8% of helmet-wearing cyclists sustained their injuries here (fig. 2).

The windscreen, including the metal framing structures (A-posts and roof edge) as well as the side structures of posts and roof of the car must be regarded as especially dangerous. Many injuries of severity grade AIS 3 were established here. Injuries to the head caused by hitting the curbstones, wall corners or trees were established with 7% of helmet wearers, but only with 1% of those without helmets (no figure).

Injuries to the head are predominately located at the front side (fig. 3). The back of the head receives relative few injuries. The head with the face region, especially the chin and forehead, is nearly always exposed to impact risks, this despite a great number of kinematic patterns in the crash and post-crash phase. Approximately one third of all injuries to the helmet-protected as well as the not protected heads of motor-cyclists are minor soft-part injuries, like contusions and abresions (32.9% respectively 32.8%) (fig. 4). More serious soft-part injuries, such as laceration-/contusions, cut or scalping injuries represent another 21.9% of helmet-protected, and 25.5% of not protected heads. Eye damages were only observed with unprotected persons. A loss of teeth could be observed with helmet-protected as well as unprotected heads. The Commotio cerebri can still be regarded as a slight injury. This injury was received by 28.8% of the helmet wearers, and 16.7% of those without helmets. Serious injuries like fractures, eye damage, Contusions, therefore represent just 16.4% of injuries to helmet-protected and 24% to the unprotected heads. Despite the fact that in our study the helmet wearers outnumbered the unprotected ones, more injuries were registered for the latter (72.5% of the total injuries). This fact clearly shows the great protective effect of the crash helmet.

The shape of the injury-causing object was predominately smooth (65.7%), and in 24.1% edged respectively arched (fig. 5). The resulting injury patterns show a distinct influence of the impact area. Fractures and cuts were found in an increasing number with edged impact areas, while contusions, abresions, and the light Commotio cerebri also were predominately caused by flat impact points.

Injuries to the head are almost evenly distributed to the front half. While the back of the head and the skull region receive only very few injuries, damages to the helmet predominately show impact points at the front half (fig. 6). Here the frequency of impact points in the forehead and chin region (40% of all clearly recognized impact points) on the right side as well as on the left side is striking. Damages to the helmet resulting from accidents could be established with 70.2% of all helmets. Of these 48.4% were slight, 13.2% deep abresions respectively cracks. In 6.9% a breaking of the exterior shell, and in 2.5% a permanent damage to the inside material was found with the inspected helmets. A tearing, respectively a breaking of the chin-strap or damage to the lock occurred in 4.4%. It must be pointed out that 13.5% of the helmet wearers lost their helmet during the crash phase, of these 0.6% prior to the primary, 7.7% after the primary, and 2.6% after the secondary head impact.

OBJECTIVE

The impact spectrum of the head established in the real accident incident does not correlate with the test standards for helmet production. In the German Federal Republic the out-of-date DIN 4848 was still in force for the quality standard of the crash helmet. It recognizes the acquired cognitions and requirements for the head protection according to SNIVELY(2), i.e. mainly the shock absorbtion in the skull region. For this the helmet-protected test-head is tested with a flat dropping weight. The remaining force must not exceed 20.000 N. However, this norm cannot be regarded as being conform with reality any longer. In the meantime the ECE ruling No. 22 (4) has been worked out. These rules are in force in the German Federal Republic since the first half of 1984. Decisive changes are: more impacts, also in the forehead and side region. With this method the helmet drops in the first impact onto a flat anvil, and in the second impact, with approximately the same point onto a round anvil. The decelerations are measured in the dropping helmet. The resulting deceleration most not exceed maximal 300 g. For the first as well as the second impact the time of 5 ms. according to 150 g is valid (4).

BIOMECHANICAL STANDARD VALUES

Some national as well as international studies have acknowledged the protective quality of helmets (1, 3, 5, 6, 8). These findings derive mainly from the accident-analytical (accident situation, impact points, damaged helmets and injuries) and the experimental field (helmet damages and helmet loading). It is the objective to correlate the characteristics (i.e. applied force) found in the test with those of the accident realities (i.e. injuries) in the continuous development of research. Due to their various fields of activities, the authors were in a position to combine the knowledge gained from the analyses of real accidents involving motor-cyclists (1, 7) with the findings from experimental tests on crash helmets (8).

METHOD OF INVESTIGATION

Within the framework of the above study four extensively documented accidents of motor-cyclists were chosen from the 'Local Accident Investigations'. It was the objective of this study to compare the damage patterns on the crash helmets with those in the test case. In the test the applied loads, impact times, impact speeds and accelerations for a helmet damage, comparable with the accident patterns were determined. It is the aim of the study to compare the damages to the helmet, and the resulting injuries and injury severities to the head in real accidents with damages and applied forces in the test, in order to evaluate the protective effect of today's helmets. Further, to sensibly modify future test standards to test and substantiate bio-mechanical limit values, and to decisively support the work of the experts.

TEST DESCRIPTION

From accident documentations as well as the damaged helmets the main impact points, damage patterns, impact objects, injury patterns and injury severities are clearly defined (table 1). The real impact constellations of head impacts with new helmets can almost identically be reconstructed on the test bench. Three integral helmets and one half-shell helmet with an outer shell of obdurated glass fibre (GFK) and polysterol foam-rubber inside were dropped on the test bench of the Battelle Institutes e.V. (Frankfurt/Main), according to the required accident conditions and ECE 22, in such a way that possibly the same damage patterns would be obtained as in real accidents.

Here the half-shell helmet hit a tree with the rear-head region. The integral helmets hit a wooden pylon with the forehead region, and a steel edge with the rear-head region, and a wall edge with the side region. The impact speed, the impact time and decelerations in horizontal, vertical, and transversal directions were measured according to ECE 22. The resulting deceleration curves were defined by this method (table 2). The impact forces were evaluated from the existing head- and helmet measurements. Finally the damages to the exterior shell and the plastic deformations of the interior shell were measured (table 2).

RESULTS OF EXPERIMENTAL SIMULATIONS

The tests showed a good conformity with the accident situation (tables 1 and 2). Only in one case the impact force (height of fall) was chosen too low, compared with the real one (example 4). Consequently, the cracking of the exterior shell could not be obtained in the test. A very good deformation impression is shown in example 1 (fig. 7), where the back of the helmet-protected head of a motor-cyclist collided with the corner of a steel plank. The plastic deformation of the helmet interior was distorted in the real accident as well as in the test case with adequate surface. The resulting course of deceleration for the head is shown in figure 8.

In order to carry out a comparable evaluation of case test and accident reality, similar deformation patterns must be assumed, as based on theoretical considerations (fig. 9) and cognitions from accident analyses (1, 8), between impact force to the head and resulting impact sequences (injuries, damages to the helmet) several impact parameters (impact point, material qualities, human qualities) essentially influence the impact effects (time, decelerations, injuries). Therefore, the too high or too low estimated deformation volume can be corrected, in order to define existing decelerations (table 3). From the test decelerations evaluations from 106 to 3.153 g resulted for the accident incident.

The comparison of examples 1 and 4 (table 2) clearly shows the different force to the head in similar impact speeds with various helmets. In example 1 for instance, the helmet made of polycarbonate (P.C.), with a wall thickness of 4 mm, impacted with the rear head region. In the dummy head a maximal resulting deceleration of 261 g was measured. In example 4, however, the helmet made of glass-fibre reinforced plastic (GFK), with a thickness of only 2 mm, collided with the side region, near the face with the corner of a wall. The measured applied forces were four times as high.

PROTECTIVE EFFECT OF THE HELMET

The construction of a customary helmet consists of a hard thermoplastic exterior shell of synthetic, a shock-absorbing interior shell of polysterol foam, and a thin interior lining.

The protective effect of the helmet is defined by its conception and quality of materials. In a head impact the helmet has to convert the impact power into deformation- or heat energy. The exterior shell has to protect against penetrating bodies. It has to distribute the aggressive energy evenly onto the projected head region and finally absorb a part of the energy by deforming. The interior has to soften the impact. As a multiple impact can occur to the same point, a softening by elastic rebound is necessary for the crash helmet, although a more effective attenuating interior would be an advantage. Because of the helmet and the qualities of the material the following physical characteristics can fundamentally be established as basic conditions of a helmet impact:-

- impact speed of the head
- impact region
- impact angle
- condition of impact area (firmness, roughness, shape)
- quality of material

DISCUSSION

The study clearly shows that the irrevocable connection of test and accident reality strived for, is possible for the evaluation of forces and injuries. The method of experimental simulations of real accident characteristics indicate kinematic proceedings, energies and decelerations during the accident phase which are the cause of certain injury patterns and injury severities. Due to the low number of single cases, the tests described here cannot provide a comprehensive analysis of possible forces. They are intended to describe the proceedings and possibilities of interpretion. A great number of tests are necessary to provide reliable evidence. For further investigations a number of case tests with new helmets will be required until the damage pattern of the real accident case is achieved. However, the four tests clearly indicate that minor injury severities were caused by such impact forces and impact decelerations that serve as border respectively test values for helmet production. The modified limit values according to ECE (150 g above 5 ms and maximal 300 g) of the test standard require modification, as decelerations exceeding 1.000 g are evidently not unusual in accident incidents. Within the framework of this study it cannot be defined which helmet materials offer the best protection. It became, however, evident that especially the impact region clearly had an influence on the resulting injury sequences. Generally all helmets have more protective effect in the back-head and side region (high rigidity, high deformable volume of the interior shell).

All test standards should be extensively adapted to the circumstances of the accident incident and to the anatomic/biomechanic conception of the head. Therefore, it seems essential to the authors to pursue the link of the medical/technical accident analysis and experimental tests. Correlating connections between mechanical evaluations (HIC, g) and resulting injury sequences (AIS) can only be defined by this method.

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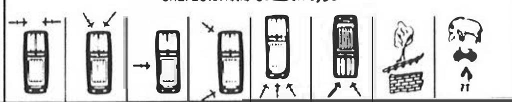
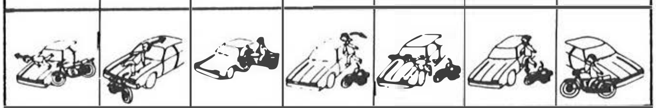


	characteristic collision type							
type	1	2	3	4	5	6	7	8
definitions: impact point on collision partner (clockwise)	11 12 01		08 09 10	02 03 04	11 12 01	05 06 07	cycle 01-12	
definitions: classification of collision-angles (Grad)	90 ± 20 270	180 ± 69	90 ± 20 270	180 ± 69 0	0 ± 69	0 ± 69	0-360	
all motorized two-wheelers	20.4	22.4	15,1	17.6	5,9	7,7	2.9	4.8

Kinematic groups for the trajectory in accidents with two-wheel riders (n=272)

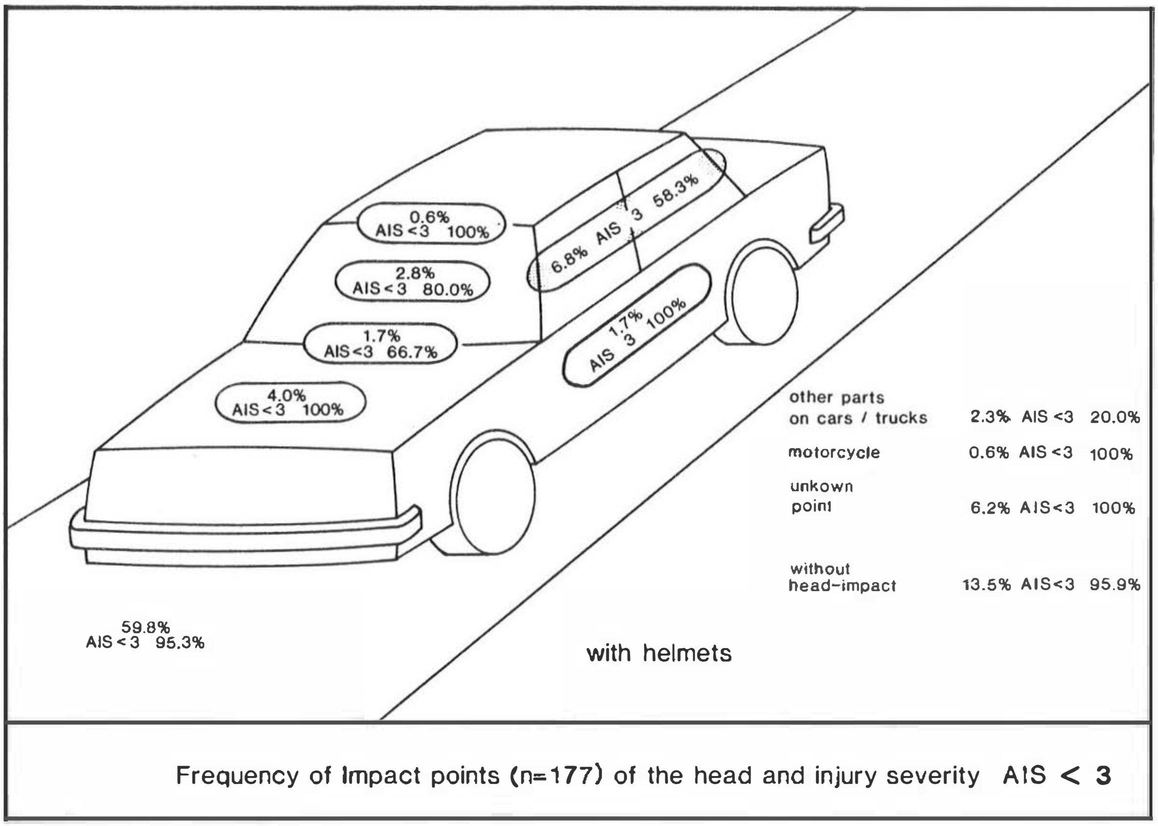
flight without impact	thrown upon the collision partner	direct impact and seated	impact on the collision partner in direction: with change	impact on the collision partner in direction: without change	slipped off the collision partner	indirect collision
A	B	C	D	E	F	G
11,8	15.1	2,9	38,4	7,7	6,3	15,1



Kind of outrun after the flying-phase of a two-wheeler

-groups-					
slipped away	roll over	small impact point	large impact point	run over	other (unknown)
-all motorized two-wheels-					
73.2	1,8	12,9	5,5	1,5	5,1

fig. 1 Collision types, kinematic and runout groups-
This classification system describes the characteristic impact- and kinematic types of the crash- and postcrash phase of a motor-cyclist during an accident.



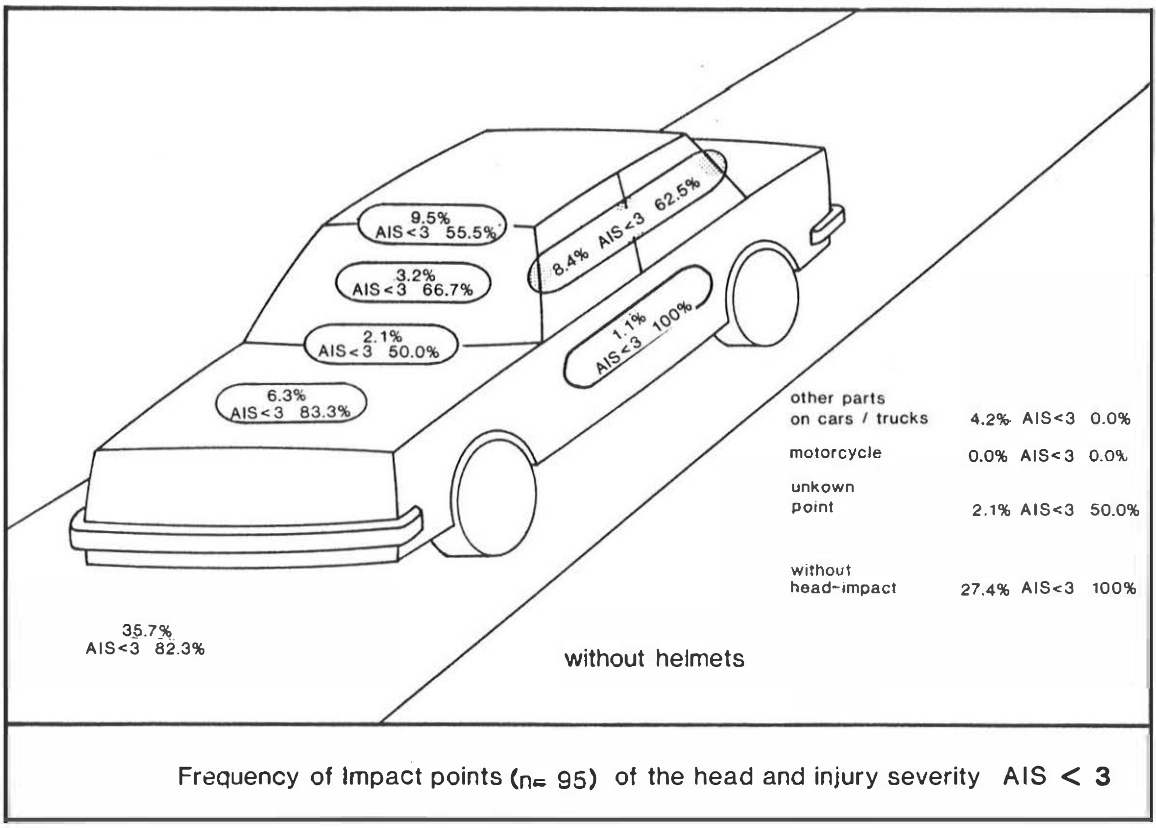


fig. 2 Impact places of injured motor-cyclists with (fig. 2a) and without (fig. 2b) helmet protection. Apart from the injury frequency (100% of all injuries), the proportion of injuries AIS < 3 is given for each impact region.

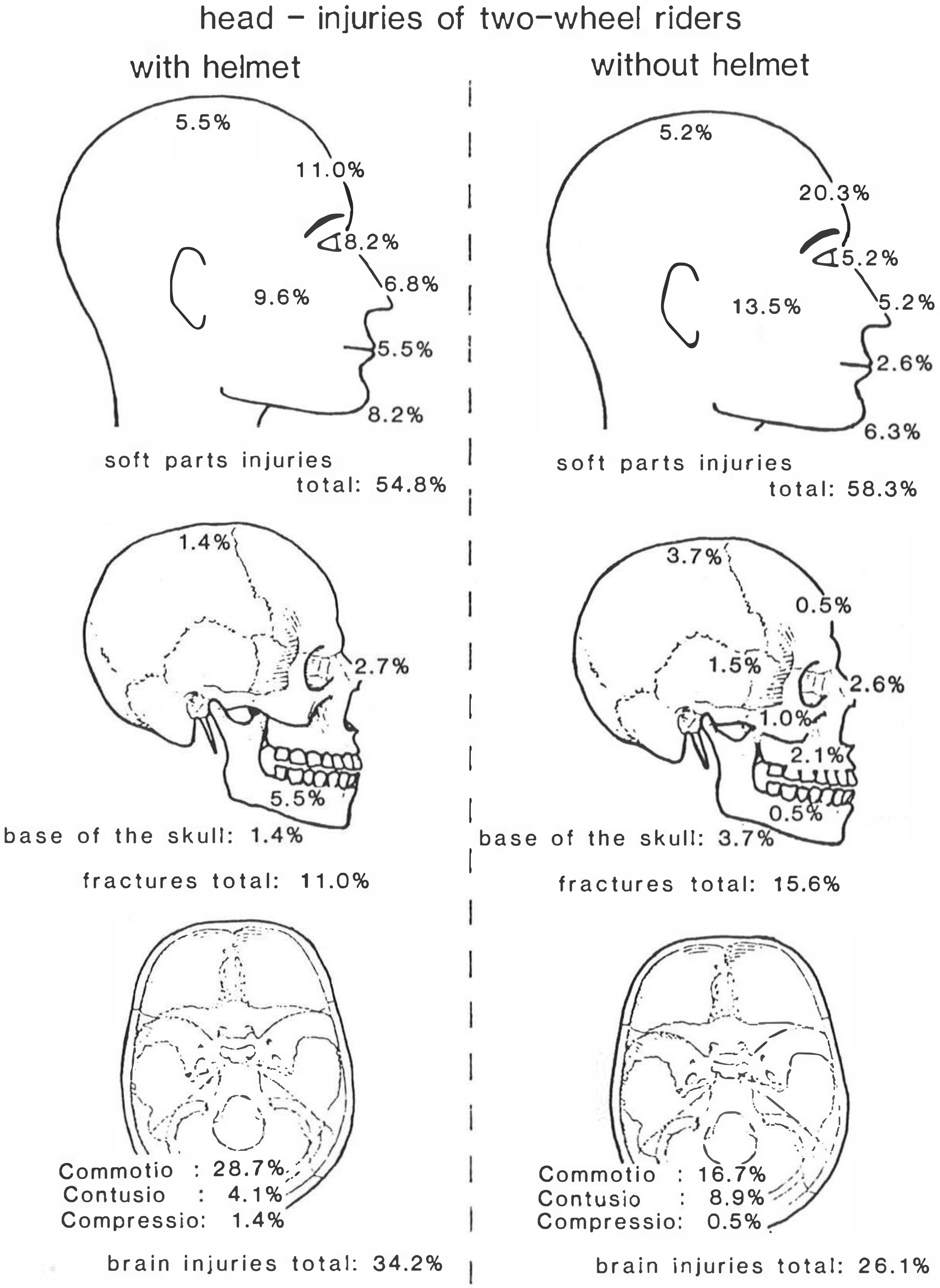


fig. 3 Localization of head injuries to motor-cyclists, divided into soft-part lesions, fractures and internal injuries

kinds of head injuries	two - wheel riders with helmet %	without helmet %	total n
bruise, abrasion	32.9 27.6	32.8 72.4	87
laceration, cut	21.9 24.6	25.5 75.4	65
eye damage	- -	0.5 100.0	1
dental damage	0.5 50.0	0.5 50.0	2
close fracture	9.6 25.0	10.9 75.0	28
open fracture	1.4 20.0	2.1 80.0	5
commotio cerebri	28.8 39.6	16.7 60.4	53
contusio cerebri	4.0 15.0	8.4 85.0	20
bursted skull	1.4 20.0	2.1 80.0	5
total	100.0 27.5	100.0 72.5	265

unknown: n = 16 persons with helmet
n = 6 persons without helmet

fig. 4 Types of head injuries for injured cyclists, with and without helmets

kinds of head injuries	kinds of head-impact smooth %	edged %	other forms %	total n
bruise, abrasion	40.2 80.5	23.4 17.2	7.4 2.3	87
laceration, cut	23.0 61.5	28.1 27.5	25.9 11.0	65
eye damage	- -	- -	- -	-
dental damage	1.2 100.0	- -	- -	2
fracture	8.0 42.4	18.8 36.4	25.9 21.2	33
commotio cerebri	22.4 73.6	18.8 22.6	7.4 3.8	53
contusio cerebri	5.2 45.0	7.8 25.0	22.3 30.0	20
bursted skull	- -	3.1 40.0	11.1 60.0	5
total	100.0 65.7	100.0 24.1	100.0 10.2	265

fig. 5 Shape of impact object for injured motor-cyclists, with and without helmet

Distribution of Impact points (n=152) on the helmets (n=166)

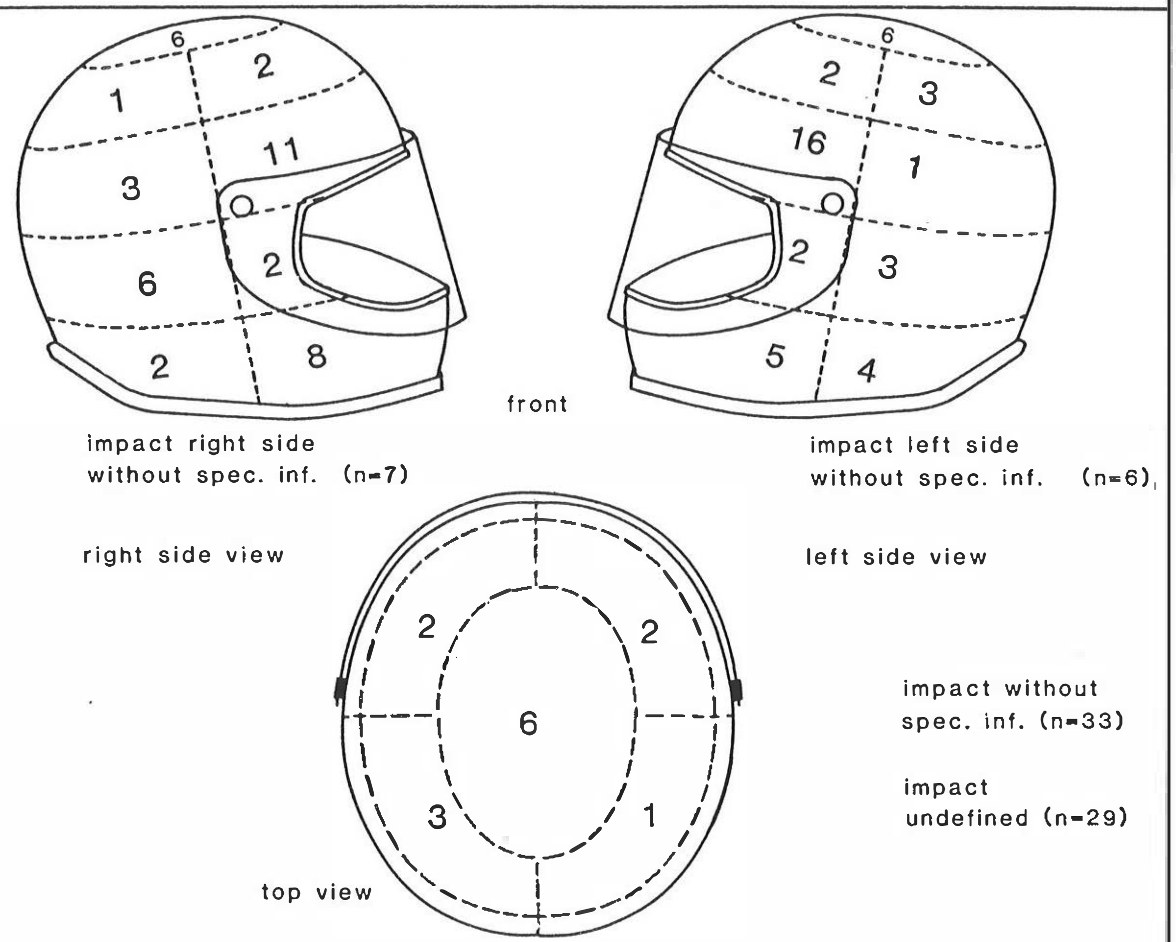
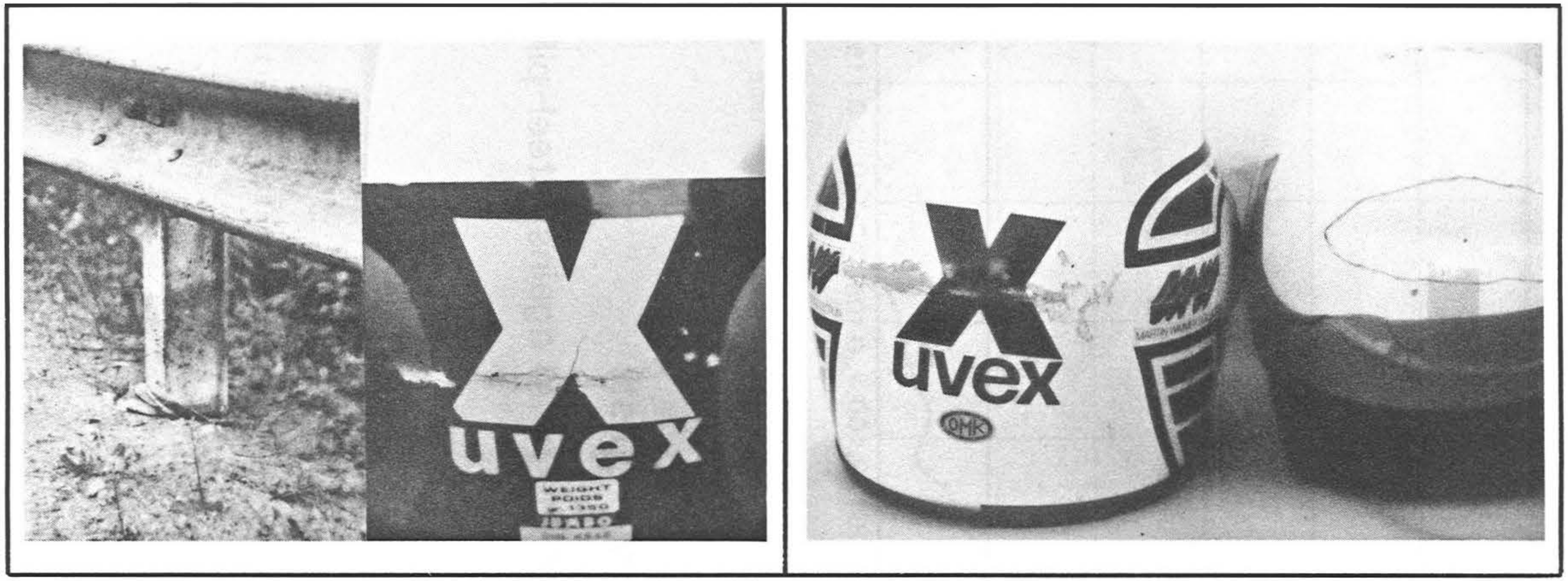
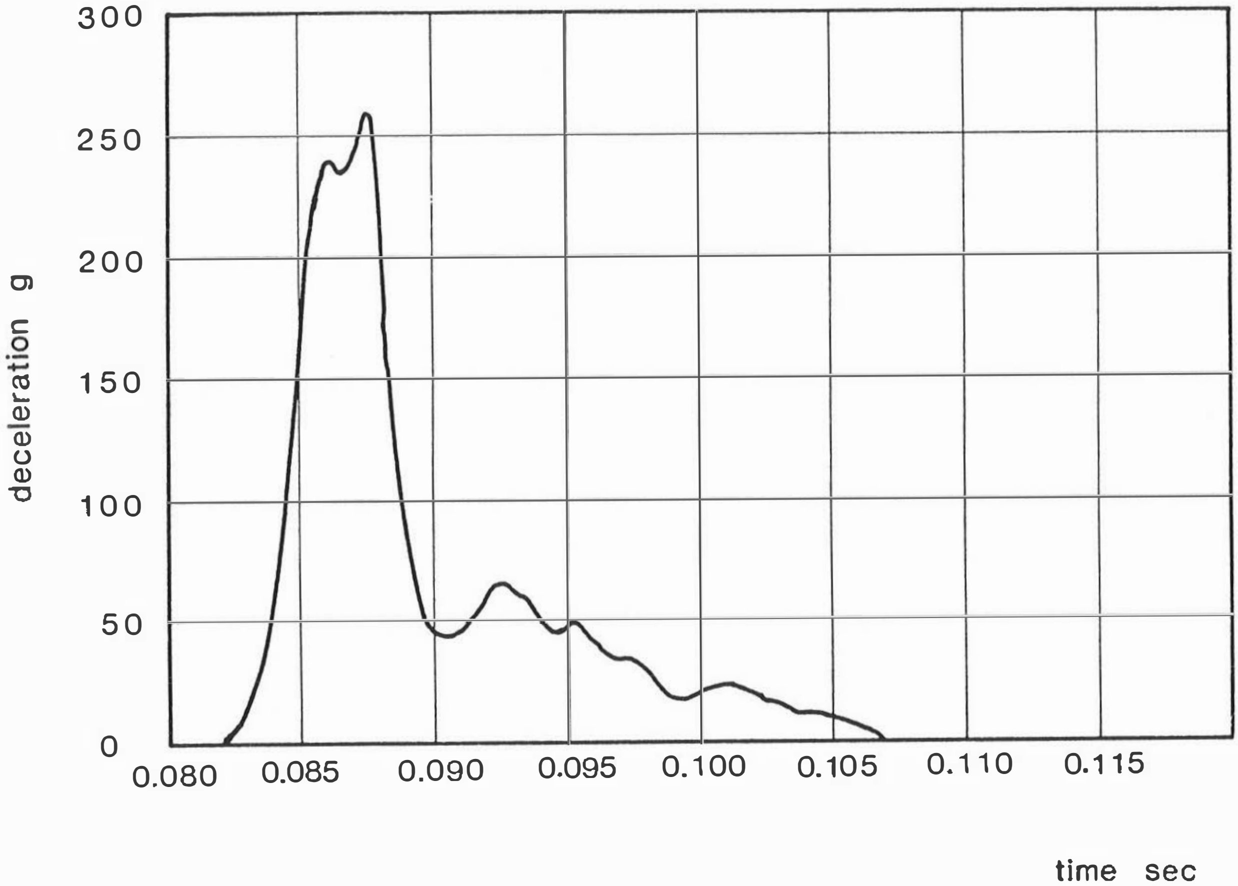


fig. 6



accident   test - result

fig. 7 Comparison between impact point and helmet damage in real accidents (both illustrations on left side) and on the test bench (both illustrations on right side)



resulting deceleration in test:

back of the head against steel-pillar

fig. 8 Timing of deceleration phase in experimental simulations

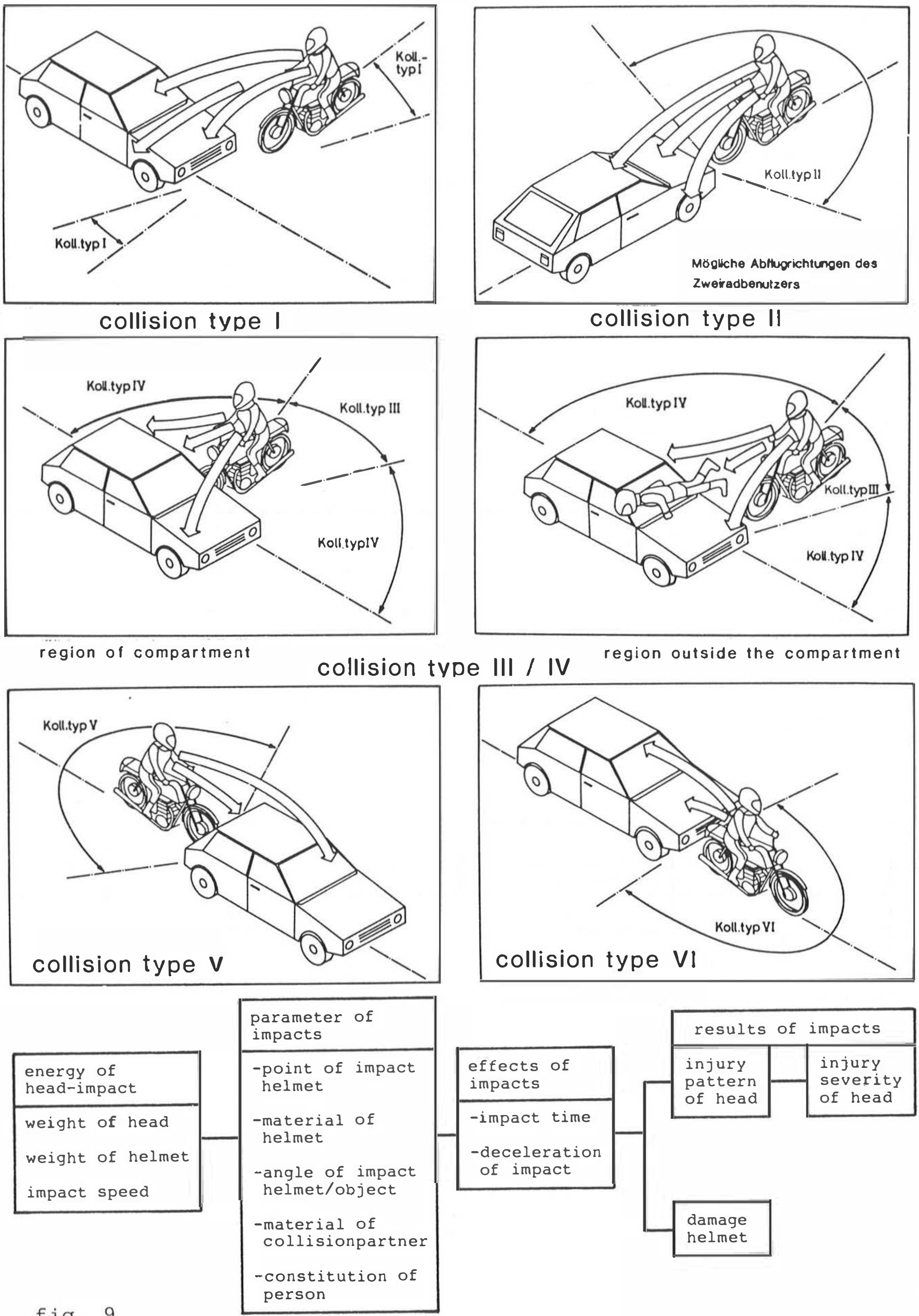

Koll.-typ I
Koll.typ I
collision type I
Koll.typ II
Mögliche Abflugrichtungen des Zweiradbenutzers
collision type II
Koll.typ IV
Koll.typ III
Koll.typIV
region of compartment
Koll.typ IV
Koll.typ III
Koll.typ IV
region outside the compartment
collision type III / IV
Koll.typ V
collision type V
Koll.typ VI
collision type VI
energy of head-impact
weight of head
weight of helmet
impact speed
parameter of impacts
-point of impact helmet
-material of helmet
-angle of impact helmet/object
-material of collisionpartner
-constitution of person
effects of impacts
-impact time
-deceleration of impact
results of impacts
injury pattern of head
injury severity of head
damage helmet

fig. 9

example	type of helmet	material outside	material inside	heaviness outside mm	heaviness inside mm	density inside g/l	impact point helmet	impact point object	damage mass -outside-	damage plane cm²	mass -inside- depth mm	mass -inside- volume cm³	injury severity of the head
1	inte-gral	gfk	poly-styrol	4	18	28	back of the head	steel-edge	deformation 12 cm	60	6	18	AIS 1
2	halve	gfk	poly-styrol	4	26	25	back of the head	tree	fissure 13 cm	62	3	13	AIS 2
3	inte-gral	gfk	poly-styrol	4	31	43	fore-head	wood-mast	fissure 10 cm	50	10	20	AIS 4
4	inte-gral	gfk	poly-styrol	2	21	41	side of the head	wall-edge	bursted	unknown	21	unknown	AIS 6

table 1 Characteristics of crash helmets and resulting injury severity grades for the head (AIS head)

example	impact weight kg	impact speed m/s	impact energy Nm	impact time ms	resulting deceleration max. g	resulting deceleration 5 ms g	damage mass -outside-	damage mass -inside- plane cm²	depth mm	volume cm³
1	5.10	10.1	260	24	261	75	deformation 12 cm	60	10	30
2	4.75	9.2	201	20	227	125	without deformation	62	1	5
3	5.05	10.1	257	14	833	20	deformation 10 cm	40	6	12
4	5.09	10.1	260	14	1051	20	fissure 4 cm	55	19	9
					base value ECE-22 300	150				

table 2 Characteristics of crash helmets defined in test cases

example	force of energy measured	force of energy critical valuation of the real energy*	maximal resulting deceleration measured	maximal resulting deceleration critical valuation of the real deceleration*	AIS head
1	260	166	261	106	1
2	201	520	227	590	2
3	257	416	833	1333	4
4	260	780	1051	3153	6
			limiting value 300 g ECE - 22		

*) factor = $\frac{\text{volume of deformation by test}}{\text{volume of deformation by accident}}$

table 3 Adaptions of measured resulting decelerations and calculated forces in comparison to real injury severities to the head according to AIS