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The occurrence of acute subdural haematoma and diffuse axonal injury as two typical acceleration injuries

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ABSTRACT

Closed head injuries have already been classified into contact injuries and acceleration–deceleration injuries. Two typical acceleration–deceleration injuries and at the same time, the two worst head injuries are acute subdural haematoma (ASDH) and diffuse axonal injury (DAI), and that is where they got their medico-legal importance. Using experiments, it has been shown that acceleration with an impact time of more than 20–25 min (which occurs in traffic accidents in real life) causes DAI, whereas an impact time of 5–10 min is more likely to produce acute subdural haematoma. The aim of this research is to show that not all, but some types of traffic accidents are more typical for the occurrence of DAI, as well as that the ASDH is not a common feature for all types of fall. The analysis conveyed covered 80 cases of closed head injuries (traffic accidents, falls and assaults) where a complete forensic medical autopsy has been undertaken, followed by a complete forensic–neuropathological examination. For the purpose of diagnosing DAI, immunohistochemistry using antibody against β-amyloid precursor protein has been involved. Results show that ASDH is more likely to occur in cases of simple fall, assaults and cyclists and DAI is more typical for vehicular traffic accidents and cases of falling from a considerable height. The paper also comprises discussion about some open questions regarding the diagnosis of DAI in the medico-legal practice.

1. Introduction

In the last 20 years, there has been a new classification of closed head injuries in two main categories: focal and diffuse,[1] and with regard to the biomechanism of their occurrence they are grouped as contact and inertial (acceleration–deceleration) injuries.[2] Contact injuries occur as a result of the direct impact to the head, and acceleration–deceleration injuries are caused by a sudden movement of the head, and the direct impact is not necessary for their occurrence as it was experimentally shown.[3] Acute subdural haematoma (ASDH) and diffuse axonal injury (DAI) are two typical acceleration–deceleration injuries which occur as a result of the acceleration to the head, with a special contribution of the rotational acceleration,[4] but differ in the duration of acceleration forces to the head.

It has been shown experimentally that ASDH is caused by relatively short duration (5–10 min) angular acceleration loading at high rates of acceleration, whereas DAI occurs most readily when the head moves coronally and it occurs when the acceleration duration is longer (20–25 min) and the rate of acceleration lower than conditions that produce ASDH.[5,6] In real life, circumstances for ASDH mostly occur during falls when the head rapidly decelerates against a firm surface, whereas the conditions for producing DAI occur in vehicle traffic accidents where impact to deformable and padded surfaces lengthens the deceleration and decreases its rate.

Nowadays, there are reported cases of DAI in the events such as falls from a considerable height,[7] falls from a simple height,[8,9] and blow,[10,11] but caution is needed for two things: first, these cases were reported prior to the widespread recognition of other causes of axonal damage, particularly ischaemia, and second the diversity of the yielded results in great part depends on the different criteria for diagnosing DAI. Also, there are studies which report almost a constant association of ASDH and DAI in traffic accident victims.[12] Here lies the necessity of revising and revitalising the discussion

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about which traumatic events are more typical for the occurrence of ASDH and which are more likely to result in DAI.

For this purpose, we analysed the occurrence of ASDH and DAI in three different types of traumatic events: traffic accidents, falls and assaults (blow). A hypothesis has been established that the occurrence of ASDH is more characteristic of cases of simple fall, blow and those types of traffic accidents associated with a rapid fall on a firm surface (cyclists), whereas DAI is more characteristic of vehicle traffic accidents and falls from a considerable height.

2. Materials and method

Eighty cases with fatal closed head injuries have been investigated with a post mortal period up to 24 h and time of survival between immediate death and 1.5 months (age ranged from 5 to 94 years, 57 males and 23 females). The information about the traumatic event in which injury occurred is given in Tables 1 and 3. All 80 cases have been analysed for the occurrence of ASDH (Table 1), and for the occurrence of DAI, only cases with time of survival of at least 2 h have been analysed (Table 3), a total of 63 cases.

Forensic medicine autopsies were performed in all cases, including the analysis of the mechanisms of injury according to the lesions on the soft and bone tissues of the head, and intracranial structures. The presence of ASDH was noted and considered as life threatening if volume of the clotted blood exceeds 50 ml.[2,13] Then a complete forensic–neuropathological examination of the fixed brain was performed[14,15] (fixed in a 10% buffered formalin solution for at least 2 weeks). After macroscopic examination of the coronal slices that has been documented on photographs, samples for microscopic examination were taken from brain regions already known as predilection for the occurrence of DAI[16,17]: the body and the splenium of corpus callosum including white brain matter adjacent to corpus callosum; capsula interna; pons and cerebellar peduncles.

For the purpose of visualisation of damaged axons, in addition to the conventional haematoxylin and eosin staining, immunohistochemical staining was performed with the application of antibodies to β-amyloid precursor protein (APP), by the method of Sheriff et al.[18]: antigen retrieval in citrate buffer (pH 5.0), incubation with antibody against β-APP (mouse anti-Alzheimer precursor protein A4 monoclonal antibody, clone 22 C 11, diluted 1:200, Chemicon International, Temecula, CA, USA) overnight at 4C. The enzyme complex used was ABC (Universal VECTASTAIN ABC-Peroxidase kit, Vector Labs, Burlingame, CA, USA) with a secondary antibody – biotinylated anti-mouse IgG (Biotinylated Anti-mouse IgG, produced in horse, Vector Labs). Diaminobenzidine (Peroxidase Substrate Kit (DAB) Vector Labs) was used for visualisation (marked for small print).

In the process of DAI diagnosing, clinical and pathological criteria were considered. The occurrence of immediate and prolonged coma was taken as a clinical criterion, and the pathological criterion was based on the grading system of Adams et al.,[19] according to which the presence of a focal lesion in the corpus callosum was regarded as DAI 2, while a focal lesion in the rostral brainstem was regarded as DAI 3. The diagnosis of DAI 1 had to be established by a microscopic finding of widespread axonal damage with traumatic pattern in the absence of any macroscopic feature.

In the histological determination of DAI, damaged axons with a typical traumatic appearance and distribution had to be seen in at least three different brain regions, of which at least one is located above and one below the tentorium.[16,17] As a 'typical traumatic appearance and distribution of damaged axons', we took the occurrence of single or small groups of swollen 'varicosity'-like β-APP positive axons or torn axons seen as 'retraction balls' diffusely distributed throughout the white matter and particularly present in the white matter bundles (Fig. 1).

The feature of circumscribed foci or a linear pattern of β-APP positive axons, frequently described as a 'zig-zag' or 'Z-shaped' pattern, which are densely distributed in one or two brain regions (most often in the pons), was considered a predominantly hypoxic-ischaemic finding and was not taken into consideration in the diagnosing of DAI[20–22] (Fig. 2).

Statistical evaluation was performed using the Pearson Chi–Square test of independence and Fisher's Exact Test for 2 by 2 tables. The significance level used is $\alpha = 0.05$.

3. Results

The occurrence of ASDH in different types of traumatic events is presented in Table 1. Evidently, ASDH is mostly found in cyclists, simple falls and cases of assault.

Statistical evaluation was made to explore the interdependence between the occurrence of ASDH and a particular category of traumatic events. One category comprises those events where the injury mechanism is closely related with a rapid deceleration on a firm surface: cyclists, simple falls and cases of blow associated with fall. The other category consists of cases with a longer duration of the acceleration forces: vehicle traffic accidents and falls from considerable height. Pedestrians have been excluded from the statistical evaluation. Statistically, a significant interdependence was shown between the occurrence of ASDH and the category of traumatic events related with a rapid deceleration on a firm surface

Table 1
The occurrence of ASDH in traffic accidents, falls and assaults.

Type of traumatic event	Total	ASDH	%ASDH
Traffic accident	61	20	33
Pedestrian	32	9	28
Cyclist	10	8	80
Motorist	5	2	40
Driver	7	1	14
Passenger	5	0	0
Railroad accident	2	0	0
Fall	16	8	50
Simple fall (<2m)	6	4	67
Fall of a height (>2m)	10	4	40
Blow-assault	3	2	67
Total	80	30	37.5

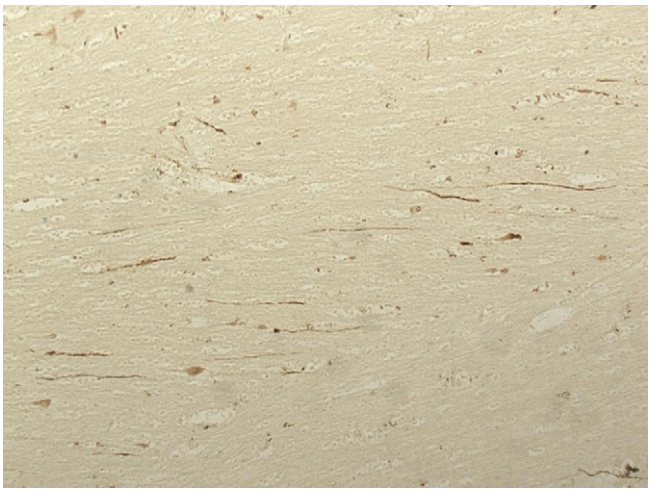

Fig. 1. Corpus calosum in a case with diagnosed DAI, with a time of survival of 8 days. Finding of scattered immunoreactive (damaged) axons along the white matter bundles, which can be also seen as fusiform swellings, thickened filaments and globules, is considered as traumatic pattern and distribution of axonal injury.

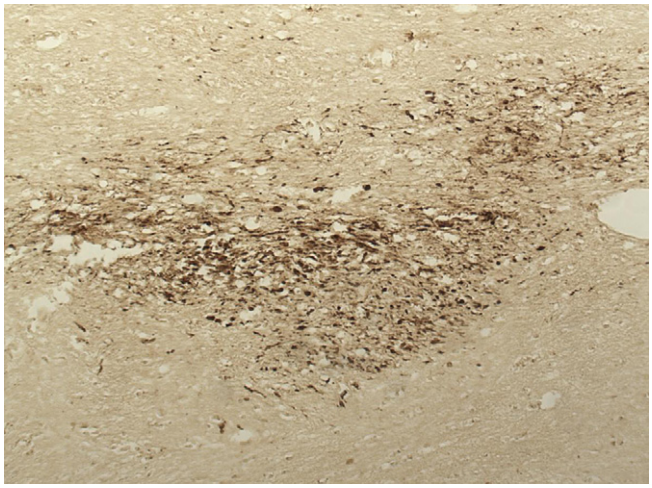

Fig. 2. Corpus calosum in a case who survived 3 days after injury. The feature of circumscribed foci of β-APP positive axons, which are densely distributed in one or two brain regions (most often in the pons) was considered a predominantly hypoxic-ischaemic finding.

(Chi square = 9.53, df = 1, $p = 0.0020$ (with Yates' correction) (Fisher's exact one-tailed test) $p = 0.000901179$), Table 2.

The analysis of the occurrence of DAI in different types of traumatic events is presented in Table 3, showing the exclusive frequency of DAI in drivers and very high incidence in cases of fall from a considerable height.

The association between the occurrence of DAI and a particular category of traumatic events has been explored statistically, showing significant interdependence between the occurrence of DAI and the category of traumatic events related with a longer duration of acceleration forces: vehicle traffic accidents and falls of a considerable height (Chi square = 7.93, df = 1, $p = 0.0049$ (with Yates' correction) (Fisher's exact one-tailed test) $p = 0.00208374$), Table 4.

We also investigated the simultaneous occurrence of DAI and ASDH in the investigated cases. Statistical analysis of the interdependence between the occurrence of ASDH and DAI did not show any statistically significant association (Chi square = 0.00, df = 1, $p = 0.9549$; Chi square = 0.00 df = 1 $p = 1.0000$ (with Yates' correction) (Fisher's exact one-tailed test) $p = 0.578002$), Table 5.

4. Discussion

Results show that ASDH was most frequently found in cases of simple fall – 67%, assault cases, where blow was often associated with fall on a firm surface – 67%, and in those kinds of traffic accidents where a great part of the injury mechanism has been attributed to fall on a firm surface, represented by cyclists – 80%. On the other side, ASDH was least frequently found in drivers – 14%, and was not found at all in passengers, which makes it an injury not so typical of vehicle traffic accidents. Results very similar to these were found in an experimental model, where 72% of ASDH were due to high strain falls and assaults and 24% were due to lower strain-rate vehicular injuries.[23] In a more recent study, where the epidemiology of injury mechanisms in ASDH and DAI was comparatively analysed, results show common occurrence of ASDH in non-vehicular cases, particularly falls – 47%, and almost exclusive occurrence of DAI in vehicular cases – 79.7%.[24]

All these data undoubtedly point to a typical occurrence of ASDH in cases of fall, and the results of the present study suggest the high presence of ASDH particularly in cases of simple fall (fall from one's own distance or up to 2 m). Similar findings have already been reported, where within the population over 65 years of age who were victims of ground-level falls, ASDH was present in 86%.[25] In addition, the results of the present study show that ASDH, besides its typical presence in falls, also occurs in those types of traffic accidents where the injury mechanism is closely related to fall on a firm surface, typically found in cyclists.

According to this, which injury will occur in one particular traumatic event, ASDH or DAI, primarily depends on a concrete injury mechanism. In this context, pedestrians are characterised with the biggest diversity regarding the injury mechanism. Some injuries occur as a result of the primary collision with the vehicle (primary injuries), while others result from getting over the vehicle or being run over by a vehicle (secondary injuries) or fall on a firm surface (tertiary injuries). There is no pure but complex injury mechanism. They both occur in short-duration and long-duration acceleration forces, and the type of the head injury will depend on which of them will predominate. That was the reason why pedestrians were excluded from the statistical analysis.

Analysing the occurrence of DAI, the results show the presence of DAI in 40% of investigated cases with a survival time of at least 2 h, its exclusive occurrence in drivers – 100% and high frequency in cases of fall from a considerable height – 60%. The overall presence of DAI in all cases with closed head injury of 40% is very similar to those reported in the early papers where DAI was initially described: 30% by Adams et al.[19]; from 30% to 50% by Gennarelli[1]; and in more recent studies: in six out of 20 cases who survived with the moderate disability[26]; in eight out of 28 young children with

Table 3
The occurrence of DAI in traffic accidents, falls and assaults.

Type of traumatic event	Total	DAI	%	AI-ish
Traffic accident	49	25	51	
Pedestrian	26	13	50	2
Cyclist	10	3	30	4
Motorist	4	2	50	1
Driver	5	5	100	
Passenger	2	1	50	1
Railroad accident	2	1	50	
Fall	11	3	27	
Simple fall (<2m)	6	0	0	2
Fall of a height (>2m)	5	3	60	2
Blow-assault	3	0	0	1
Total	63	28	44	13

Table 2
Association between the occurrence of ASDH and a particular category of traumatic events, categorized according to the mechanism of injury.

Type of traumatic event	ASDH	noASDH	Total
VTA and FCH	7 (14,58%)	22 (45,83%)	29 (60,42%)
Cyc, FSH and Assault	14 (29,17%)	5 (10,42%)	19 (39,58%)
Total	21 (43,75%)	27 (56,25%)	48 (100%)

VTA- vehicle traffic accidents; FCH – falls from a considerable height; Cyc – cyclists; FSH – falls from a simple height.

Table 4
Association between the occurrence of DAI and a particular category of traumatic events, categorized according to the mechanism of injury.

Type of traumatic event	DAI	noDAI	Total
VTA and FCH	12 (32,43%)	6 (16,22%)	18 (48,65%)
Cyc, FSH and Assault	3 (8,11%)	16 (43,24%)	19 (51,35%)
Total	15 (40,54%)	22 (59,46%)	37 (100,00)

VTA – vehicle traffic accidents; FCH – falls from a considerable height; Cyc – cyclists; FSH – falls from a simple height.

Table 5
Comparative presentation of the occurrence of ASDH and DAI in the investigated cases.

	ASDH	no ASDH	Total
DAI	13 (20,63%)	15 (23,81)	28 (44,44%)
noDAI	16 (25,4%)	19(30,16%)	35 (55,56%)
	29 (46,03%)	34 (53,97%)	63 (100%)

non-accidental injury[27]; and in 58% of cases with closed head injury who survived at least 1 month.[28]

Analysing the occurrence of DAI through the prism of traumatic event, the results of the present study are in accordance with the literature, showing the most typical occurrence of DAI in vehicle accidents[5,24] and cases of fall from a considerable height.[7] It was not detected in the cases of a simple fall or in the assault cases, besides the fact that isolated and sporadic cases of simple fall and assault cases with a diagnosed DAI have been reported on several occasions.[8–11] In this context, one should be aware that the diversity of the yielded results in great part depends on the different criteria applied in the process of the diagnosing of DAI and equalising DAI with axonal injury (AI) of any aetiology but traumatic. Diagnosing DAI without using immunohistochemistry (antibody against β-APP or antibody against the neurofilament[17,29]) or diagnosing it on the basis of the feature of damaged axons in one or two brain regions, does not fulfil the present day standards for diagnosing DAI.[22,30] Using β-APP immunochemistry, AI can be detected in cases with post-traumatic survival times of less than 60 min and a minimum of 35 min[31] However, it must be emphasised that the detection time of APP is variable and the assessment must be careful. The β-APP intensity increases with time up to 24 h. After that, the staining may become more granular, slightly pale after a few days and disappears after around 1 month or less. When the post-traumatic survival time exceeds 24 h, in the assessment of the axonal damage one can include antibodies for visualisation of cellular reaction also: CD68 for microglia and glial fibrillary acidic protein (GFAP) for astrocytes. Before the introduction of immunohistochemistry, axonal damage was mostly visualised using histochemistry methods such as Bielschowsky's silver stain, by which damaged axons could have been seen after at least 18 h of survival.

Furthermore, nowadays there are criteria regarding the appearance and distribution of damaged axons that is indicative of traumatic origin.[20,21] By all those criteria, DAI can be diagnosed by the presence of damaged (immunoreactive) axons with a typical traumatic appearance and pattern in three or more different brain regions, of which at least one is located above and one beneath the tentorium (Fig. 1).

Furthermore, the traumatic pattern of the damaged axons should not be confused with an ischaemic feature (Fig. 2).

Hence, wide sampling of the brain and the proper interpretation of β-APP immunoreactivity can determine the cause of AI in most cases (not all of them), but it must be emphasised that the evaluation of DAI in traumatic events should be always correlated with histopathology and clinical context.

As it has been stated before,[17] we have very few cases of DAI documented this way for cases of assault and simple fall, which implies the necessity of medico-legal precautions in the process of reconstruction of the injury mechanism.

Ultimately, the results of the present study do not suggest any association or any significant simultaneous occurrence of ASDH and DAI, as they have been reported.[12] Results show that approximately half of the cases with ASDH would have simultaneous occurrence of DAI also, and half of the cases with DAI would also show the presence of ASDH. These two types of acceleration injuries and, at the same time, two most serious injuries to the head, in real life, obviously occur as a result of separate conditions. The occurrence of ASDH is almost always associated with a rapid deceleration against a firm surface, typically seen in falls, blows associated with falls and traffic accidents associated with fall (cyclists) and DAI is mostly produced by longer duration of acceleration forces to the head, almost exclusively in cases of vehicular traffic accidents.

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None declared.

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Conflict of interest
None declared.

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