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PAPER

PATHOLOGY/BIOLOGY

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Pontomedullary Lacerations in Falls from a Height—A Retrospective Autopsy Study*

ABSTRACT: Brainstem pontomedullary laceration (PML) in falls from a height appears as isolated cases and usually in feet-first impacts with a ring fracture. The aim of this study was to determine the frequency of PML in falls from a height, as well as the frequency of concomitant head and neck injuries. Out of 261 cases, PML was present in 40. An impact to the chin, as well as a feet- or buttocks-first impact, most often led to PML owing to transmission of the impact force. Also, a lateral, frontal, or posterior head impact, with subsequent hinge fracture, as well as the frontoposterior hyperextension of the head associated with an upper spine fracture, could be possible mechanisms of PML in falls from a height. The jawbone and other facial bones act as shock absorbers, and their fracture diminishes energy transfer toward the skull and protects the brain and brainstem from injury.

KEYWORDS: forensic science, forensic pathology, brainstem injury, pontomedullary laceration, falls from a height, skull base fracture, impact area

Falls from considerable height are common in suicides and in some accidents, and they may rarely be homicidal as well (1). The velocity of the fall at the moment of reaching the ground is calculated as $V = \sqrt{2gh}$, where g is gravitational acceleration (9.81 m/s^2) and h, the height fallen from (2). The frequency, pattern, and extensiveness of injuries resulting from falls from a height are determined by body weight and its velocity at the moment of impact, the nature of surface impacted, the duration and intensity of the impact force, the body orientation at the moment of impact, and the elasticity and viscosity of the tissue of the contact body region (3,4). It also depends on the age of the victim, the clothing, and the composition of the ground (4). When falling, injuries are caused as a result of direct impact and/or transmitted force. The nature and type of injuries primarily depends on the height from which the body has fallen (5).

The heights of many of the falls and the recognized association between the height of the fall and the severity of the injury probably explains the large number of unsurvivable injuries. These injuries principally involved the thoracic aorta, heart, brain, and brainstem, all owing to the very rapid deceleration seen in other high energy impacts (6). The head injuries frequently seen in falls from a height include subarachnoid, intra- and extradural hemorrhage, intracerebral hemorrhage, and brain contusions, as well as severe disruption and the complete or partial loss of brain structures (4). Some studies show that the frequency of head injuries is highest in falls from a height of below 7 m and from over 30 m, which could be explained by the specific body orientation and the fact that primary head impact is the most frequent. In falls from a height of over 30 m, associated with greater forces, the increased frequency of head injuries may be the result of the primary impact, the expected secondary impact, and the transmission of force (3).

Brainstem injuries have been reported in cases of vehicle drivers and passengers, pedestrians and motorcycle, and bicycle riders, but also in high falls (4,7). Brainstem lacerations may be either partial or complete and are associated with hinge or ring fractures, or fractures of the cervical spine—almost always with immediate death (7).

The aim of this study was to determine the frequency of brainstem pontomedullary lacerations (PMLs) among victims fatally injured owing to falls from a height, as well as the frequency of concomitant cranial, facial, and cervical spine injuries in such cases, and through all of these, to establish a possible underlying mechanism of PML in cases of falls from a height.

Material and Methods

This retrospective autopsy study was performed over a 7-year period (from 2002 until 2008). The information contained in this study was derived from a review of autopsy records, police reports, and heteroanamnestic data. All cases and injuries were caused by the free-fall model of high fall (both jumps and accidental falls were included in the study) onto a solid surface. Also, all cases in which cause of death was other than blunt force injury (e.g., drowning) were excluded from the study in order to make the sample as homogenous as possible in terms of injury mechanism. Children under the age of 15 years were not included in the study because of the different biomechanical properties of a child's body.

A total of 391 autopsy records of victims injured attributing to falls from a height, either suicidal or accidental, were analyzed.

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There were 280 cases with some form of severe head injury (brain contusions, skull, and other cranial fractures—that is, head injuries of Abbreviated Injury Scale ≥ 3)—after which we excluded an additional 19 cases with extensive destruction of the head. In this way, we formed a sample of 261 cases of victims injured attributing to falls from a height, which we further analyzed.

Out of those 261 cases, we formed a subgroup of the 40 cases with a laceration in the junction between the pons and the medulla oblongata—PML. In all of these cases, the PML was partial and the depth varied from *c.* 4 to 8 mm. In order to define the specific PML injury mechanism, we did not include cases where the rupture occurred caudally or rostrally of this junction, including the distal parts of the medulla oblongata or the pons, as well as the cerebral crura. The cause of death in this subgroup was PML, and all the victims died at the scene before admission to the hospital.

The height of the falls ranged from 0 to 75 m. In each case, the height was either already determined in police records or estimated through the number of floors of the building—the height of each floor was assumed to be 3–3.5 m, according to the established standard. The sample was therefore divided into three groups: low falls up to 7 m, high falls from 7 to 30 m, and very high falls above 30 m.

The data retrieved included the following: gender, age, height of fall, the presence of brainstem PMLs, and concomitant head injuries—brain contusions; skull, jawbone, and upper cervical spine fractures; and local soft tissue injuries of the head. To understand the mechanisms by which PML occurs, we classified the head impact areas into frontal, lateral, parietal, posterior, and chin area, depending on the injuries to the soft tissue of the head and scalp, as well as facial and cranial fractures and the distribution of brain contusions. The frontal impact area included the forehead and frontal parts of the face, bonded by the zygomatic and buccal regions above the upper lip. The posterior impact area included the occipital region, as well as the posterior part of the parietal region. The parietal region included the close surrounding of the parietal suture projection on the top of the head. We defined the lateral impact area as the region between the previously determined frontal, parietal, and posterior impact area. We regarded the chin region as a specific impact area because of its possible explanation of the PML mechanism. In cases with more than one clearly established impact area, we considered the main impact area to be the one with most severe injuries owing to the application of greater force. If there were no obvious external head injuries, we considered these cases to be without any direct head impact.

The data obtained were analyzed using Pearson's chi-square test, the Mann–Whitney test, binary logistic regression, and Spearman's correlation coefficient for estimating relationships because all the variables show nonparametric distribution (which was tested using the Kolmogorov–Smirnov test for normal distribution). A p-value of <0.05 was considered significant and <0.01 was highly significant. The SPSS software version 17.0 (license number 106454; SPSS, Inc., Chicago, IL) was used for statistical analysis.

Results

A total of 391 autopsy records of victims injured owing to high falls, either suicidal or accidental, was analyzed. Of those, 280 (71.6%) had some form of head injury, and after excluding 19 cases with extensive head injury, we finally formed a sample consisting of 261 subjects, which was statistically analyzed. This group was composed of 202 men and 59 women. The average age was 38.2 ± 15.8 years (range: 17–95 years). In the analyzed sample group, 142 cases were accidents and 119 cases were suicides.

The distribution of different types of head and upper spine injury in the observed group and in the subgroup with PML is presented in Table 1. The distribution of different types of isolated skull base fractures with regard to the different head impact area in the observed group and in the subgroup with PML is presented in Table 2. The sample distribution according to the height of the fall, for the whole sample and for the PML subgroup is presented in Table 3.

Partial PMLs were present in 40 cases (15.3%) out of the total of 261 head injuries, which breaks down into 25 men and 15 women, the average age was 47.2 ± 18.3 years (range: 20–79 years). In 30 cases, the manner of death was suicide and in 10 cases accident.

There were statistically more men than women in the whole sample group, but not in the PML subgroup, with the male/female ratio at 3.4:1 and 1.7:1, respectively ($\chi^2 = 78.349$, $p < 0.01$; $\chi^2 = 2.500$, $p = 0.114$).

Discussion

When a person falls or jumps from a height, the body may fall while maintaining the same orientation to the ground but it usually twists and turns in an unpredictable manner (1). Injuries from falls arise from vertical decelerative forces during direct impact, secondary impact from objects intervening during the descent or after the initial impact, and energy transfer to sites remote from the impact site (2). At the moment of impact, a falling body undergoes deceleration and the amount of kinetic energy transferred to the ground reacts with an equal amount against the body. Injuries result from the resorption of the lost energy (3). Bouncing on impact occurs when falling from great heights (2). The primary impact is usually the site of the most severe injury (1).

Head impacts tend to occur in accidental falls of adults because the body's center of gravity is in the upper body. Skull fractures and brain injuries can be observed in isolation. Secondary impacts after striking the ground account for head injuries in other landing positions (2). Head injuries dominate in fatal falls regardless of the height. Fatal head injuries dominated in falls below 7–10 m and above 25–30 m (3,8).

In our sample, PML was present in a significant number victims fatally injured owing to high falls: 40 out of the 261 cases with head injuries (15.3%). If we observe the subgroup with PML by itself, all the head impact areas were almost equally distributed ($\chi^2 = 4.100$, df = 5, $p = 0.535$). Hinge fractures were most often seen in this subgroup, as well as an absence of skull base fractures ($\chi^2 = 29.400$, df = 3, $p < 0.01$).

There are only a few studies that consider PML occurrence, and practically, none of them consider falls from a height, which

TABLE 1—*The distribution of different head injuries in the entire observed group and the subgroup with brainstem lacerations.*

	Whole Sample (261 Cases) (%)	With Brainstem Laceration (40 Cases) (%)
Brain contusions	198 (76)	11 (28)
Fractures of calvaria	194 (74)	25 (63)
Fractures of skull base	197 (75)	31 (78)
Jawbone fractures	22 (8)	2 (5)
Upper spine fractures	19 (7)	10 (25)
Local injuries of chin area*	49 (19)	11 (28)
Fractures of facial bones	77 (30)	9 (23)

*Includes abrasions, bruises, and wounds.

TABLE 2—*The distribution of skull base fractures with regard to different head impact areas in victims injured owing to falls from a height in the entire sample. The values in brackets represent the number of subjects with PML.*

	Head Impact Area						
Skull Base Fracture	None	Chin	Frontal	Lateral	Posterior	Parietal	Total
None	5 (2)	7 (5)	27 (1)	12 (0)	9 (0)	4 (1)	64 (9)
Isolated pyramids fracture	0	1 (0)	0	0	0	0	1 (0)
Hinge fracture	4 (3)	2 (1)	17 (6)	22 (7)	12 (6)	1 (1)	58 (24)
Ring fracture	4 (3)	1 (1)	1 (0)	0	7 (2)	0	13 (6)
Other	0 (0)	1 (0)	38 (1)	54 (0)	32 (0)	0	125 (1)
Total	13 (8)	12 (7)	83 (8)	88 (7)	60 (8)	5 (2)	261 (40)

PML, pontomedullary laceration.

TABLE 3—*The distribution of different height of the fall in the entire observed group and the subgroup with brainstem lacerations.*

Height of Fall	Up to 7 m	7–30 m	Above 30 m	Total
Whole sample	106	119	36	261
PML subgroup	1	22	17	40

PML, pontomedullary laceration.

appear as isolated cases and usually in feet-first impacts with a ring fracture of the skull base (4,7,9–11). Research into traumatic brain injury using physical models and animal experiments has shown that a force resulting in angular acceleration primarily produces diffuse brain damage, while a force causing exclusively translational acceleration produces only focal brain damage (12). The underlying mechanism of the brainstem PML is still unclear, and there are several theories. One of the most accepted mechanisms for PML postulated so far is the hyperextension of the head owing to a face or forehead impact, as well as anteroflexion and torsion (11,13). However, newly proposed mechanisms include chin impact with the transmission of the force toward the skull base (7). Some other proposed mechanisms include shearing lesions owing to differences in acceleration and deceleration of the cortico-medullar junction and a parietal temporal or occipital impact, or sometimes even without any head impact at all (11,13–15).

In our study, binary logistic regression showed that the impact area on the head together with the specific skull base fracture type was statistically significant predictors of PML occurrence or absence ($B = -1.709$, Wald = 98.955, $p < 0.01$, for the whole model), with skull base fracture being a slightly better predictor that impact area (for skull base fractures, Wald = 60.443, df = 4, $p < 0.01$; for the impact area, Wald = 46.781, df = 5, $p < 0.01$). Impacts in the lateral (seven out of 88) and frontal (eight out of 83) regions of the head were associated with the absence of PML. On the other hand, chin impact—seven out of 12—and the absence of a direct head impact—eight out of 13 cases—were good predictors of the occurrence of PML. Chin impacts lead to the violent movements of the head, causing instantaneous craniocervical dislocation, which leads to the indirect lesion of the brainstem, most often PML, because the junction of the pons and the medulla oblongata is anatomically the thinnest part of the brainstem and thus the weak spot (7). The absence of a direct impact in the head is probably owing to indirect force action after a feet- or buttocks-first impact. In these situations, the impact force is transmitted up the spinal column and upper vertebrae, and telescopically intruded into the skull, causing brainstem laceration (1,2).

Similar mechanisms after a chin or feet- and buttocks-first impact also lead to specific skull base fractures—ring and hinge fractures. As mentioned before, in our sample, binary logistic regression showed that skull base fractures were statistically significant predictors of PML occurrence or absence (Wald = 60.443, df = 4, $p < 0.01$). The best predictor of PML occurrence was the ring fracture, followed by the hinge fracture (Table 2). On the other hand, the absence of a skull base fracture, as well as the group of other skull base fractures, were good predictors of PML absence.

As mentioned before, in a chin impact, kinetic energy is transmitted through the mandible and temporomandibular joints toward the skull base and the brain (7). In a feet- or buttocks-first impact, energy is transmitted up the spinal column and the upper vertebrae, toward the foramen magnum and brain (1,2,16). In cases of a chin impact, we can see that the most of them were associated with the absence of a skull base fracture and some were associated with an isolated pyramid fracture, hinge, or ring fracture. More than a half of these cases were associated with PML. Also, in cases without a direct head impact, that is, in feet- or buttocks-first impact, there was an almost equal distribution among skull base fracture absence, ring, and hinge fractures, with more than a half of these cases associated with PML. In both of these situations, there is some kind of gradation of impact force transmission. This could mean that the impact energy was often sufficient to produce PML, but insufficient to produce a skull base fracture. These results are somewhat consistent with a similar study of PML occurrence in car occupants after frontal collision (7). The skull has a specific architecture that naturally protects the brain and the organs of the face. The main components of this architecture are pillars and arcs formed by the denser parts of the cranium that absorb most shocks. The force needed to produce a skull fracture is highly variable. Parameters such as the stiffness of the impact surface, the height of the fall, the weight of the victim, the angle of the impact, and the localization of the impact can all influence this force (17). In our study, if we observe the type of skull base fracture, we can assume that the smallest amount of absorbed kinetic energy leads to an isolated pyramid fracture, a larger amount to a hinge fracture, and further increases in energy leads to a ring fracture, in both chin and feet- or buttocks-first impact. Further increases in impact energy would lead to massive fracture, often a scalp laceration and possibly the extrusion of the brain (1). It seems that the type of skull bone fracture correlates with the height of the fall, with heights over 7 m being associated with a higher frequency of multifragmental fractures (3).

In our observed group of 261 subjects, hinge fractures were most often associated with lateral (22 cases), frontal (17 cases), and posterior (12 cases) head impacts, with a similar distribution in the PML subgroup (Table 2). In these cases, the PML followed the fracture line that separated the skull base into two halves. The occurrence of PML in these cases could depend on the impact energy, but even more so on the position of the fracture line, and less on head movements (7).

Facial bone fractures are common in high falls—both mandibular fractures and other facial bones fractures. One of the previously published studies showed that, out of 505 persons with facial bone fractures, 129 were caused by falls and 69 had an isolated mandibular fracture (18). When we analyzed the subgroup of persons with chin impacts, it was demonstrated that mandibular fracture decreases the possibility of PML occurrence (Fisher's exact test $p = 0.010$). Also in the subgroup with frontal and facial impacts, the fracture of other facial bones also significantly decreases the possibility of PML occurrence ($\chi^2 = 7.296$, $p = 0.007$). Jawbone and facial impacts lead to the deceleration of the head and the rotational acceleration of the brain and, with sufficient impact energy, they lead to brain rotation and deformation and, after exceeding a certain threshold, to eventual brainstem injury (19). There is controversial data about concomitant facial bone fractures and brain injuries (20–23), but our results showed that in cases of fatal falls from a height, the jawbone and facial bones have the function of shock absorbers, protecting the brain and brainstem from excessive kinetic energy transfer and injury.

In high falls, a compression fracture of the vertebrae is frequently observed (16). Upper spine fractures are common in high falls, most often in the form of atlanto-occipital and atlanto-axial joint dislocation/fracture (24). Several studies have demonstrated an association between traumatic brainstem lesions and craniocervical injuries, but mostly in traffic accident victims (9,11,25). In our sample, fractures and dislocations of the upper spine, including the atlanto-occipital joint, were significantly associated with PML ($\chi^2 = 21.977$, $p < 0.01$). That also indicates frontoposterior hyperextension of the neck as a possible mechanism of brainstem injury. This result is statistically significant, regardless of the fact that posterior neck dissection was not routinely performed during the autopsy in all the examined cases. While the upper spine functioned as a damper and energy absorber protecting the brainstem from injury in fatally injured car occupants (7), that was not the case in victims fatally injured owing to a fall from a height.

Our study showed that pontomedullary laceration was present in a significant number of victims fatally injured in falls from a height (15%). There are several possible mechanisms of pontomedullary laceration in such cases. An impact to the chin, as well as a feet- or buttocks-first impact, with or without a skull base fracture, most often led to this fatal injury owing to the transmission of the impact force, either through the jawbone or the vertebral column. Also, a lateral, frontal, or posterior head impact, with subsequent hinge fracture and pontomedullary laceration, as well as the frontoposterior hyperextension of the head associated with an upper spine fracture, could be possible mechanisms of brainstem injury in falls from a height. The jawbone and other facial bones act as shock absorbers, and their fracture diminishes energy transfer toward the skull and protects the brain and brainstem from injury.

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