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Death by hanging: a retrospective case-control investigation of the intervertebral disc vacuum phenomenon on PMCT

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Abstract
During hanging gravitational forces affect the spine. Intervertebral vacuum phenomenon (VP) implies that gas accumulations in the discs are caused by degeneration of the spine and trauma. It was hypothesized that VP detected on postmortem computed tomography (PMCT) has a higher incidence in hanging deaths, which can be correlated to age, degenerative spinal changes and type of hanging (complete-incomplete). Secondly, it was investigated whether the presence of Simon's bleedings is related to hanging type and VP on PMCT. A retrospective hanging case-control study of 72 cases was conducted. PMCT data were evaluated by two observers for the presence of VP and its localization within the thoracic and lumbar discs, and for any degenerative changes of the spine. Autopsy protocols were assessed for the presence of Simon's bleedings during autopsy. VP did not statistically differ among hanging and control cases but it was statistically correlated to complete hanging, increasing age and degenerative spinal changes. Centrally located VP within the discs was correlated to hanging, especially complete hanging, and younger ages, contrary to control cases that showed gas at the disc periphery. Simon's bleedings were correlated with complete hanging and centrally located VP. Centrally located VP within the discs increases the probability for complete hanging, while increasing age and degenerative changes reduce this probability. Intervertebral VP is multifactorial radiological entity. The presence of centrally located VP can indicate that hanging could be considered as an alternative mechanism of death and that great forces and loads may have affected the spine perimortem, especially with decreasing age and when Simon's bleedings are present.

Keywords Virtopsy · Postmortem computed tomography (PMCT) · Complete hanging · Incomplete hanging · Simon's bleedings · Intervertebral disc vacuum phenomenon

Introduction

Hanging is a frequent method of suicide [1, 3] whereby the body is suspended on a band around the neck [1–3]. Depending on whether the body is freely hanged or not, hanging is divided in two subtypes. In complete hanging the feet have no contact with a surface, whereas in incomplete hanging, part of the lower body, such as the knees or feet, partially

support the weight of the body [1]. A short drop (0.5–1 m) is associated with a lower prevalence of cervical spine injuries. Long drops (about 4–5 m) cause frequent cervical spine injuries and even decapitation [4–6]. Death then is caused by any combination of a constriction of the carotid or vertebral arteries, venous occlusion, stimulation of the carotid sinuses, obstruction of the airways leading to asphyxia, and injury of the cervical spine with spinal cord disruption [1–3, 7].

In cases of hanging convulsions, decortication rigidity with extension of the trunk and the lower limbs, and isolated muscle movements may occur within a very short time [8, 9]. Suspension of the body by the neck, especially by complete and long-drop hanging [6], seems to provide gravitational and load effects that affect the vertebrae in particular. A typical injury is the Hangman's fracture of the second vertebral body [5, 6, 10, 11]. Occasionally, injuries of the thoracic spine have also been reported in the literature [12]. Gravitational forces apply along the line of the vertebral bodies [5, 6, 12] affecting

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all parts of the vertical spine. These vertebral spine injuries may affect ligaments, intervertebral discs, and bones.

Simon's bleedings (SB) are stripe-like bleedings in the anterior longitudinal ligament, typically found in the lumbar spine at autopsy. They may be found more frequently in young people, [13] or their presence may be independent of age and age-related changes of the vertebrae [14]. They are neither a reliable vital sign nor are they specific: they can appear in other forms of asphyxiation, after blunt force trauma to the spine, in cardiac death and hypothermia [15].

Two mechanisms of SB are considered: agonal convulsions, and gravitational traction. The lumbar spine, especially between the fifth vertebra and the sacrum, is the most flexible part of the spine with regard to extension and flexion [16] where just a few agonal convulsions appear to be sufficient to cause SB [11, 16]. However, gravity must have been the defining mechanism for the SB identified in 3 of 4 hanging cases with decapitation [17].

This study investigated the correlation between hanging and gas accumulations, described as vacuum phenomenon (VP), found radiologically in intervertebral discs. VP and SB are both believed to share, at least in part, a traumatic mechanism of origin. As humans cannot metabolize nitrogen gas, excess nitrogen may be cleared from tissues passively via diffusion into the blood. Boyle's law can provide a physical explanation for the phenomenon: "if an enclosed space, like a joint, is allowed to expand, the volume within the enclosed space will increase. By expanding the volume the pressure within the space falls". According to Henry's law "the solubility of the gas enclosed in the space will decrease as the pressure of the space decreases and decreased solubility allows gas to leave solution and expand into the larger space" [18]. Thus, any trauma or pathology that induces expanding of the joint spaces, like rostrocaudal traction of the column, may potentially lead to gas accumulation and VP in the intervertebral discs [19]. The already generally low blood perfusion of the synovial membranes [18] decreases with age [20, 21]. Thus, with increasing age, macroscopic gas deposition in joint or intervertebral disc may be manifested in the form of VP after pressure is applied [19, 22].

A number of mechanisms have been associated with pathogenesis of VP, such as bone and ligament trauma, infectious processes, malignancies (like multiple myeloma [19, 23] and metastasis), effusions within the joint spaces, and iatrogenic factors like operative and invasive local activities and steroid medication [24]. The presence of VP appears to correlate with age [19, 25] and advanced stages of vertebral disc degeneration [26], particularly over the age of 40 [27].

Computed tomography is particularly useful to assess VP in vertebral discs [28]. Postmortem computed tomography (PMCT) has been investigated for its capacity to detect gas collections, also in precise amounts [29, 30] where gas can be related to trauma [30–32], resuscitation [33], or putrefaction [34]. With increasing post mortem interval, gas can increasingly be detected on PMCT [34]. Resuscitation is also associated with thoracic vertebral trauma [35]. However, CT may not always reveal relevant pathologies or subtle trauma of the spinal ligaments [36].

In this study the authors hypothesized that fatal hanging cases would show a higher frequency of VP in the thoracic and lumbar intervertebral discs than non-hanging deaths. Secondly, it was proposed that VP, possibly being of multifactorial origin, would correlate with both the individual's age and the severity of vertebral degeneration. Thirdly, it was proposed that the type of hanging (complete vs. incomplete) would influence the prevalence of VP on PMCT and the appearance of SB at autopsy, as larger gravitational forces affect the spine in complete hanging. Finally, as the etiology of VP and SB seems to be similar, it was proposed that their presence would be correlated to each other.

Materials and methods

This was a retrospective case-control study. All 48 hanging cases from the last 4 years (January 2013–July 2017) that had undergone PMCT in our facility were identified. Twelve of these 48 cases were excluded as they either had resuscitation and/or putrefaction [37] as possible causes of gas accumulations.

Thirty-six ($N = 36$) hanging cases remained (age: 42.5 ± 15.1 years, twenty-six (72.2%, 42.97 ± 16.8 years) males, ten (27.8%, 41.4 ± 9.99 years) females). Eleven (31%) had been found in freely suspended hanging positions (complete hanging) while 25 (69%) were partially suspended (incomplete hanging). Thirty five (97.2%) of them had undergone conventional autopsy after PMCT; one incomplete hanging had received no autopsy after PMCT.

A control group of decedents that had undergone autopsy was taken from the same period (January 2014–June 2017). Thirty-six cases were randomly selected, with an age-sex match (within ±2 years for each case). Criteria for selection were no signs of mechanical trauma or decomposition and reported absence of resuscitation measures.

Each group was then split in two age groups (each $n = 18$), one group for ≤43 and one for >43 years of age. The cut-off age value of 43 years old was selected as it provided equality of the age groups in our sample and also because of its closeness to the age of 40, which, according to the literature, is the age correlated with a higher incidence of VP [27].

The responsible forensic pathologist for each case estimated the time of death during the external examination [1–3]. The time interval between death and PMCT was 34.4 ± 29 h (range: 6 to 98 h) for the hanging group and 31.8 ± 30.4 h (range: 5 to 144 h) for the control group. PMCT was

performed on a 128-slice scanner (SOMATOM Definition Flash, Siemens Healthineers, Erlangen, Germany), with the bodies in a supine position, using automatic dose modulation (CARE Dose 4D™, Siemens Healthineers, Erlangen, Germany). The imaging parameters used were as follows: tube voltage 120kVp, slice collimation 128×0.6 mm [38]. PMCT image reconstructions of the head and neck, as well as thorax and abdomen, were also performed [38], with a slice thickness of 1.0 mm and increment of 0.6 mm.

Statistical analyses were performed with Excel (Microsoft Excel, 2016 Microsoft Corporation, USA), SPSS (IBM, SPSS 20, Chicago, IL, USA) and JMP (SAS Institute, Cary NC, USA) to obtain Chi-Square tests, Fisher's Exact Test and to fit Generalized Linear Models (GLM). *P*-values below 0.05 indicated statistical significance, and values above were considered to be not significant (n.s.).

Review of the PMCT data of all the 72 cases in this study for the presence or the absence of VP, its localization within the thoracic and lumbar discs, and for the assessment of the degenerative spinal changes, was performed by two readers (a forensic pathologist with 10 years and a trainee with 1.5 years' experience in postmortem forensic radiology) on bone kernel reconstructed sagittal and coronal MPR views. All autopsy protocols were evaluated for documented SB.

The presence of VP was registered for every case with gas within one or more intervertebral discs across both the thoracic and the lumbar spine. Both readers evaluated the presence of VP independently.

Location of gas inside the intervertebral discs was classified as either anteroposterior or craniocaudal. The categories used for both are detailed in Fig. 1. This classification was based on the assumption that VP located in the center and VP located in the periphery of the discs (along both craniocaudal and anteroposterior directions) may have different biomechanical causes.

Degenerative changes were rated by consensus reading of both readers. Due to a lack of CT related grading systems [39], grading systems for plain radiography were used [39] (Table 1.).

A formalin fixed specimen of a lumbar intervertebral disc from a 62-year old woman that had been found incompletely hanged, with VP located centrally in the disc, was examined histologically to document any tissue correlations.

Results

Inter-rater agreement for the presence of VP in all 72 cases was good (Cohen's Kappa 0.78; $p < 0.0001$).

An overview of the findings is given in Tables 2 and 3 and Figs. 2, 3, 4, and 5.

Hanging-VP on PMCT

Hanging cases did not have a significantly higher count of VP (21/36) than control cases (19/36) (Figs. 2a and 3).

After separating cases into complete hanging versus the rest of the cases studied (controls and incomplete hangings), VP was found in 91% of complete hanging cases compared to 49% of incomplete hanging and control cases (Chi-Square $p < 0.006$) (Figs. 2b and 3).

Comparing both age groups for the presence of VP across both hanging and control groups, there was 27/36 (75%) VP in the older age group (>43) but only 13/36 (36%) in the younger group (Fisher's Exact Test $p = 0.0008$).

Increasing age correlated with increasing VP. Within the younger group (≤43), 44% of the hanging cases showed VP whereas controls only contained 28%. In the older group, 72% of hanging cases and 78% of controls had VP (n.s.) (Figs. 2c and 4).

A General Linear Model (GLM) resulted in logistic functions that described the observed probability of free hanging in our data as function of both presence of VP and age (whole model test $p = 0.02$) (Fig. 6). Thereby, the presence of VP (scaled 0 to 1) increased the possibility that a case had been one of free hanging (z-axis) whereas increasing age mildly reduced this probability. The mere presence of VP (without consideration of categories describing VP location within intervertebral discs) yielded a maximum probability for hanging of ~35%. Therefore, further differentiation of VP into location categories was required to better understand the phenomenon in the context of hanging,

VP and specific location within intervertebral disc to correlate with hanging

Dividing the cases in which VP was present into three categories of VP localization within an intervertebral disc (Fig. 1) for two dimensions (anteroposterior and craniocaudal) provided further insight.

For the cases with anteroposterior VP, the controls with VP in categories I (63%), II (26%) and III (11%) slightly differed from the hanging cases with categories I (33%), II (33%) and III (33%) (n.s.). Craniocaudal categorization differentiated the controls into categories I (79%), II (0%) and III (21%) that significantly differed from hanging with categories I (38%), II (19%) and III (43%) (Chi-Square, $p < 0.009$) (Fig. 3).

Using the merged group of higher category VP locations ("Central VP") for anteroposterior and craniocaudal directions, central VP was found in 52% of the hanging (both complete and incomplete) vs. 16% of the control cases (Fisher's Exact Test, $p = 0.012$) (Figs. 2d and 3). A subdivision into younger and older individuals (cut-off 43) yielded a particularly high prevalence of central VP in hanging, particularly in the younger group (Chi-Square
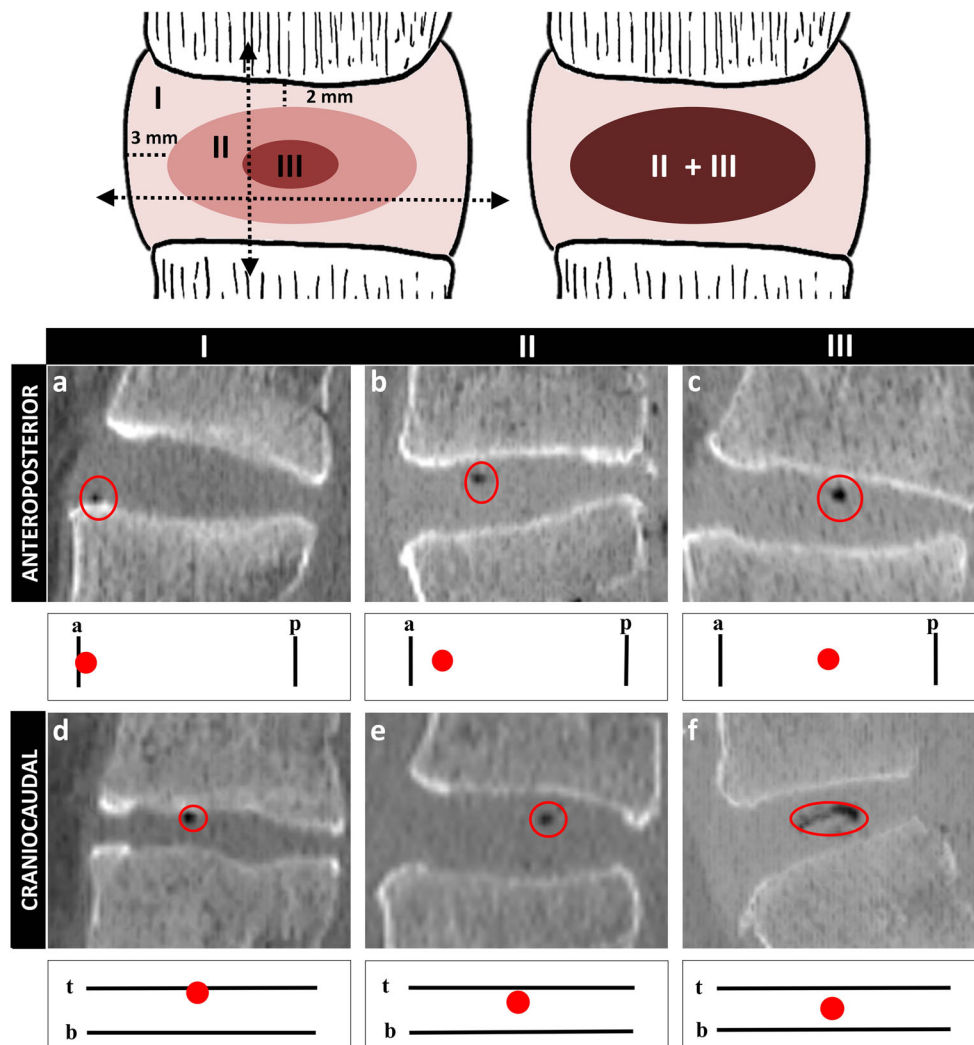
Fig. 1 The location of VP was categorized into three classes with regard to two directions (dotted arrows, diagram on the top), the anteroposterior (**a**, **b**, **c**) and the craniocaudal (**d**, **e**, **f**) within the intervertebral discs. Anteroposterior categories: category I denotes a VP located at the anterior (a) or posterior (p) margin of the intervertebral disc as shown in **a** and as generalized in a diagram below **a**. Category II describes a slightly but not quite centered VP located close to (within a 3 mm zone), but not at, the anterior or posterior margin of the intervertebral disc (**b** and diagram below). Category III contains VP located in a center region, midways between anterior and posterior margin of the intervertebral disc (**c** and diagram below). Craniocaudal categories: category I describes a VP immediately adjacent to a border plate of a vertebral body (**d**, generalized diagram below). Category II denotes VP slightly distanced from the body plate of the vertebral body (2 mm zone), but not in the center of the intervertebral disc (**e**, diagram below). Category III then constitutes VP with a center location with regard to the craniocaudal dimension (**f**, diagram below). Where several instances of VP were present in a given case, the highest rating was noted for that case. To reduce complexity, VP classified at least in category II, if not III, along *both* directions, was then classified as "central VP" (right diagram on the top)

$p < 0.04$ (Figs. 2f and 4). Younger (0%) and older controls (21%) showed less VP than younger (62%) and older (46%) hanging cases.

For complete hanging, central VP was 90%, versus 17% in controls and incomplete hanging (Fisher's Exact Test $p < 0.0001$) (Figs. 2e and 3).

Table 1 Radiographic grading systems of lumbar disc degeneration. Osteophytes and intervertebral disc width were graded into four classes each (0, 1, 2, 3) [40]. Endplate sclerosis was graded into three categories (0, 1, 2) [41]

Endplate sclerosis [41]	Intervertebral space narrowing [40]	Osteophytes [40]
0 = None	0 = None	0 = None
1 = Either endplate	1 = Definite (mild)	1 = Small
2 = Both endplates	2 = Moderate	2 = Moderate
	3 = Severe (complete loss of joint space)	3 = Large

Table 2 Information and findings related to each single hanging-case

Case	Gender	Age	Hanging type	Simon's bleedings	VP presence	VP a/p	VP c/c	Central VP	Endplate sclerosis	Space narrowing	Osteophytes
1	M	19	Incomplete	No	No	–	–	–	0	0	0
2	M	20	Incomplete	No	No	–	–	–	0	0	0
3	F	20	Complete	Yes	No	–	–	–	1	1	1
4	M	25	Incomplete	No	No	–	–	–	0	0	0
5	M	25	Incomplete	No	No	–	–	–	0	0	0
6	M	25	Incomplete	No	Yes	1	1	No	1	1	0
7	M	25	Complete	Yes	Yes	3	3	Yes	2	1	0
8	M	28	Incomplete	No	No	–	–	–	0	0	0
9	M	29	Incomplete	No	No	–	–	–	0	0	1
10	M	31	Incomplete	Yes	No	–	–	–	0	0	1
11	M	31	Incomplete	No	No	–	–	–	0	0	0
12	F	32	Incomplete	No	Yes	1	1	No	1	0	0
13	F	38	Incomplete	No	No	–	–	–	0	0	0
14	M	40	Incomplete	No	Yes	1	1	No	1	0	0
15	M	40	Complete	Yes	Yes	3	3	Yes	2	2	0
16	F	40	Complete	Yes	Yes	2	2	Yes	1	1	0
17	F	42	Complete	Yes	Yes	3	2	Yes	11	1	2
18	M	43	Incomplete	Yes	Yes	3	2	Yes	0	0	0
19	M	44	Incomplete	Yes	Yes	3	1	No	1	1	0
20	M	44	Incomplete	No	No	–	–	–	0	0	0
21	F	44	Complete	No	Yes	1	3	No	0	1	0
22	F	45	Incomplete	No	No	–	–	–	1	1	1
23	M	47	Complete	No	Yes	3	3	Yes	2	1	2
24	M	47	Incomplete	No	No	–	–	–	0	0	0
25	F	47	Incomplete	No	Yes	1	1	No	0	1	1
26	M	50	Incomplete	No	Yes	2	3	Yes	0	0	0
27	F	50	Incomplete	–	No	–	–	–	0	0	1
28	M	53	Incomplete	No	Yes	1	1	No	2	1	2
29	M	54	Incomplete	No	Yes	2	1	No	0	1	0
30	F	56	Complete	Yes	Yes	2	3	Yes	2	2	2
31	M	58	Complete	No	Yes	2	3	Yes	2	2	3
32	M	59	Incomplete	No	No	–	–	–	1	0	1
33	M	59	Incomplete	No	Yes	1	2	No	2	1	1
34	M	69	Complete	No	Yes	2	3	Yes	2	3	3
35	M	76	Incomplete	No	Yes	2	1	No	2	3	3
36	M	76	Complete	No	Yes	3	3	Yes	2	3	3

Order of the cases according to ascending age

Type of hanging-VP on PMCT

Among the three groups (control, incomplete, and complete hanging cases), distribution of VP location categories, both in the anteroposterior and craniocaudal direction, differed (Figs. 2g, h and 3).

Frequencies of craniocaudal location (complete hanging with VP in categories I (0), II (20%) and III (80%), incomplete hanging with categories I (73%), II (18%) and III (9%), controls with categories I (79%), II (0%) and III (21%), Chi-Square $p < 0.0001$) (Figs. 2g and 3) and distribution of anteroposterior location categories of VP (complete hanging: I (10%), II (40%), III (50%); incomplete hanging: I (55%), II (27%), III (18%); controls: I (63%), II (26%), III (11%), Chi-Square, $p < 0.05$) (Figs. 2h and 3) differed significantly between groups.

Using the "Central VP" category, controls (positive 16%), incomplete hanging (18%) and complete hanging

Table 3 Information and findings related to each single control-case

Case	Gender	Age	VP Presence	VP a/p	VP c/c	Central VP	Endplate sclerosis	Space narrowing	Osteophytes
1	M	18	No	–	–	–	0	0	0
2	M	19	No	–	–	–	0	0	0
3	F	21	No	–	–	–	2	1	0
4	M	23	No	–	–	–	0	0	1
5	M	23	No	–	–	–	0	0	0
6	M	23	No	–	–	–	1	0	0
7	M	26	No	–	–	–	0	0	1
8	M	29	Yes	3	1	No	2	2	1
9	M	29	No	–	–	–	0	0	0
10	M	31	No	–	–	–	1	0	0
11	M	31	Yes	1	1	No	2	1	0
12	F	30	Yes	1	1	No	0	0	1
13	F	38	Yes	1	1	No	0	1	1
14	M	42	No	–	–	–	0	0	0
15	M	42	Yes	1	1	No	1	1	2
16	F	41	No	–	–	–	1	0	0
17	F	42	No	–	–	–	1	1	1
18	M	43	No	–	–	–	2	1	2
19	M	44	Yes	1	1	No	2	1	2
20	M	44	Yes	2	3	Yes	0	1	3
21	F	45	Yes	2	3	Yes	2	1	2
22	F	45	Yes	1	1	No	2	1	1
23	M	47	Yes	3	3	Yes	2	2	1
24	M	48	No	–	–	–	2	1	1
25	F	47	Yes	2	1	No	2	2	3
26	M	51	Yes	1	1	No	2	1	2
27	F	50	No	–	–	–	1	1	1
28	M	53	No	–	–	–	2	2	2
29	M	55	Yes	1	1	No	2	2	1
30	F	58	Yes	1	1	No	2	1	3
31	M	57	No	–	–	–	1	1	1
32	M	60	Yes	1	1	No	2	2	3
33	M	60	Yes	2	1	No	1	1	2
34	M	71	Yes	1	1	No	2	2	3
35	M	74	Yes	1	3	No	2	2	3
36	M	78	Yes	2	1	No	2	2	3

The order of the cases is based on the age-sex match with the hanging cases of Table 2

(90%) differed significantly (Chi-Square $p < 0.0001$) (Figs. 2i, 3 and 7).

VP on PMCT-Simon's bleedings in autopsy

SB were found with increasing frequency in controls (0), incomplete (13%) and complete hanging cases (54%) (Chi-Square $p < 0.0001$) (Fig. 2j).

VP location categories differed significantly with respect to absence versus presence of SB for both anteroposterior location categories (absent SB (VP category I (58%), II (30%) and III (12%); present SB (categories I (0), II (28%) and III (71%); Chi-Square, $p = 0.0009$) (Figs. 2k and 5), and for craniocaudal location categories (absent SB (I (67%), II (3%) and III (30%)) and present SB (I (14%), II (42%) and III (42%)), Chi-Square, $p = 0.0057$) (Figs. 2l and 5).

VP in context of degenerative changes of the spine

The pesence of VP was significantly correlated with three aspects of degenerative changes to the spine: the degree of sclerosis of the body plates (Chi-Square $p < 0.0001$),
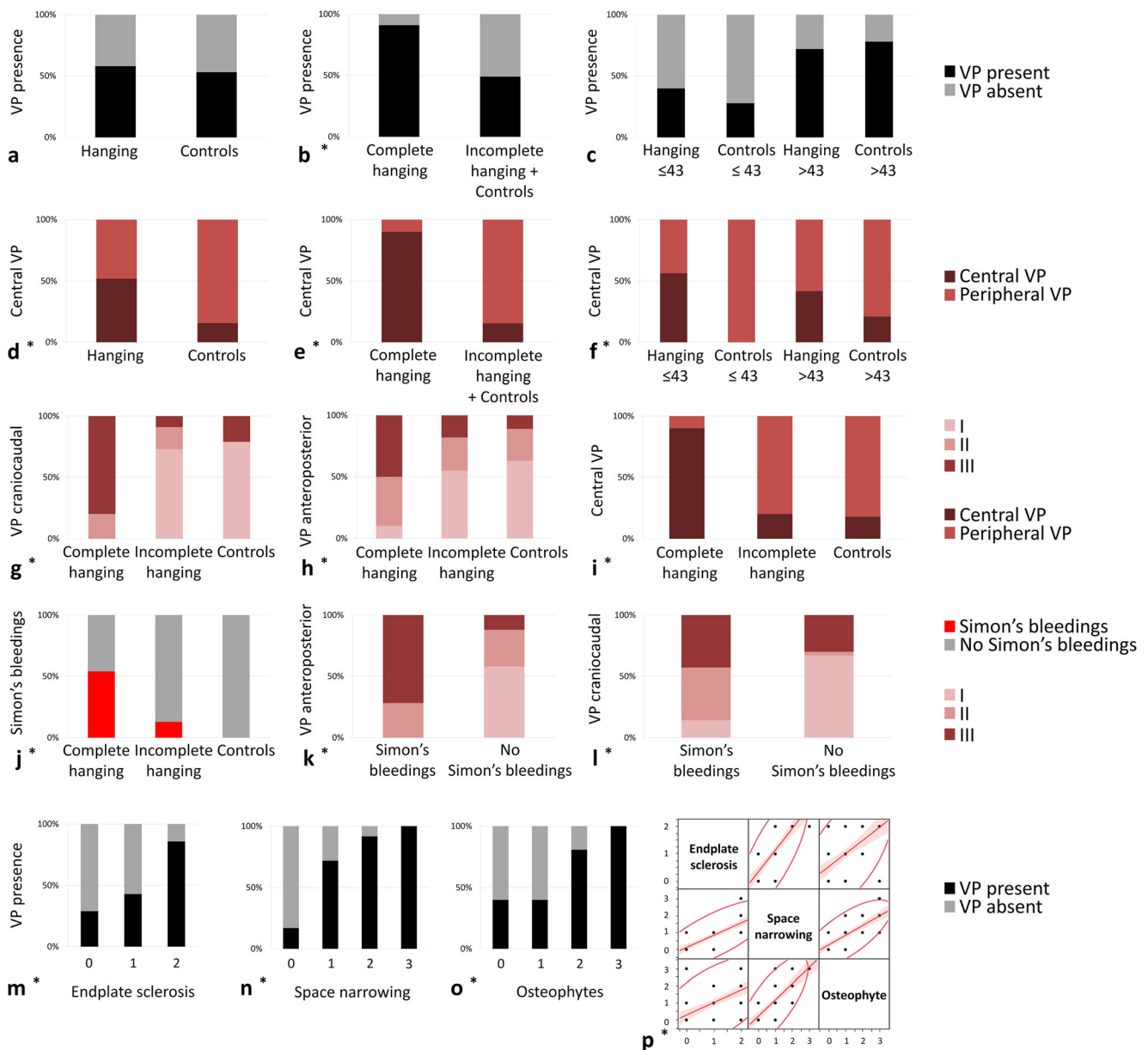
Fig. 2 Stars (*) denote results with statistical significance. – **a** The mere presence of VP in hanging cases was not significantly higher than in controls. **b*** Complete hanging correlated with a significantly higher percentage of VP than found in controls or incomplete hanging. **c.:** Age-separation of both hanging and control groups showed that VP presence was more frequent in older people, as a statistical trend, but not with significance. **d*** Significant predominance of centrally located VP in hanging cases over controls. **e*** Complete hanging correlates most with central VP localization. **f*** The higher grade VP localizations were distributed unevenly over the age groups, with central VP being more frequent in hanging groups despite smaller differences between age groups. **g*, h*** Percentages (y-axis) of VP category in relation to group

(x-axis). **g*** More central craniocaudal VP location correlates with hanging and there, more with complete hanging than incomplete. **h*** The same pattern emerges with the anteroposterior location classification. **i*** Percentages (y-axis) of coalesced VP categories. **j*** The cases of free hanging showed more frequent Simon's hemorrhages than the cases of incomplete. **k*, l*** Categories for VP location in relation to the absence or presence of Simon's bleedings. **m*, n*, o*** Correlation of the degree of degenerative vertebral body plate sclerosis (**m*** x-axis), of intervertebral space narrowing (**n*** x-axis) and of degenerative osteophyte presence (**o*** x-axis) and VP presence (y-axis). **p*** Collinearity of the severity of the three different types of observed degenerative spine changes

intervertebral space narrowing (Chi-Square $p < 0.0001$) and the osteophyte classification (Chi-Square $p < 0.0001$) (Fig. 2m–o, Table 4). These were also collinear; Pearson correlation coefficients between osteophyte grading and intervertebral space narrowing ($r = 0.73$), osteophyte

grading and body plate sclerosis ($r = 0.59$) as well as intervertebral space narrowing and body plate sclerosis ($r = 0.76$) were high and so a degenerative change index (DG index) was obtained by summing up all three scores (Figs. 2p, 6 and 7, Table 4).
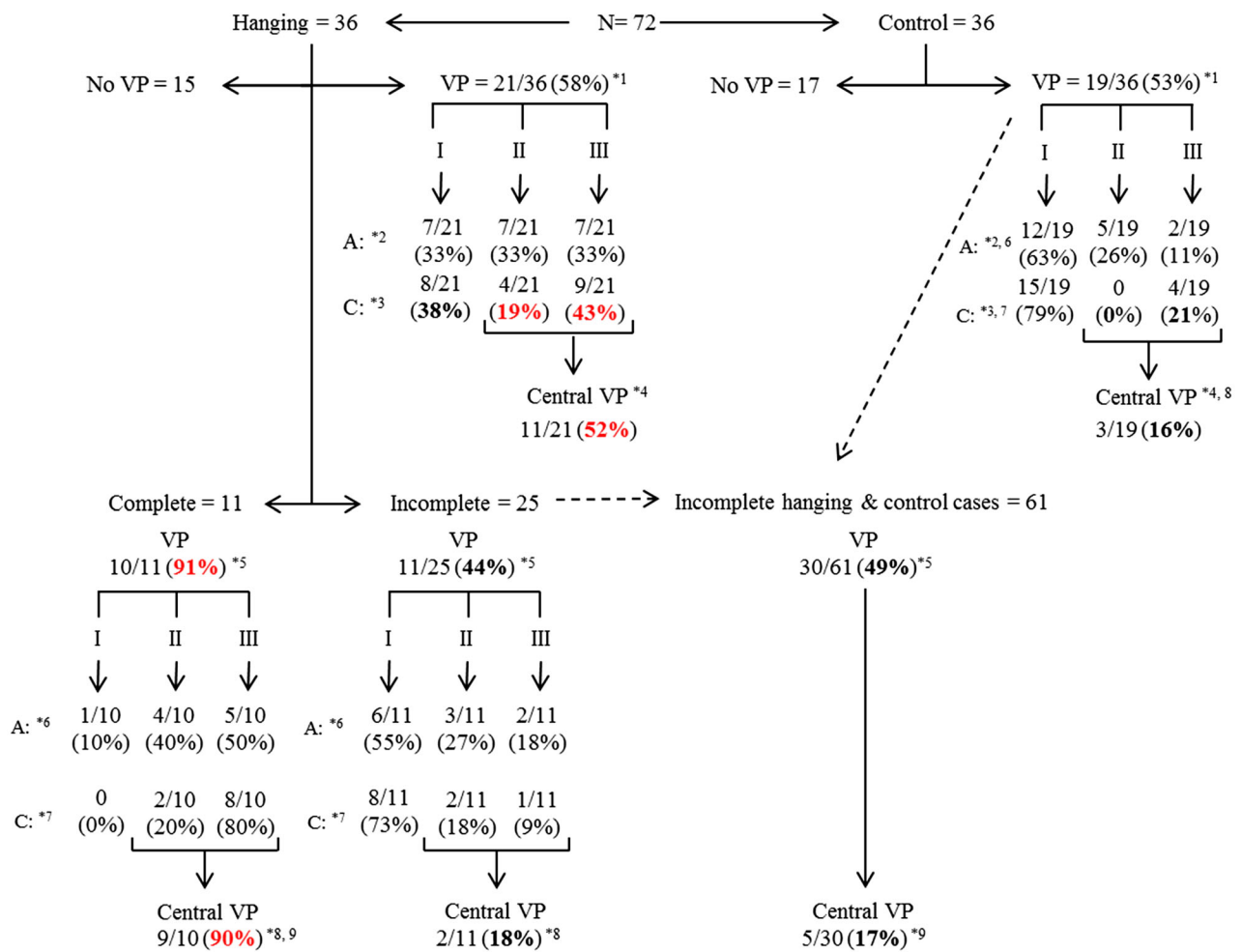
*[1, 2] Chi-Square Test not statistically significant (p>0.05), *[3, 5, 6, 7, 8] Chi-Square Test statistically significant (p < 0.05), *[4, 9] Fischer's Exact Test statistically significant (p < 0.05)

Fig. 3 Overview diagram depicting the results regarding VP incidence and its localization categories with respect to hanging and control cases and type of hanging
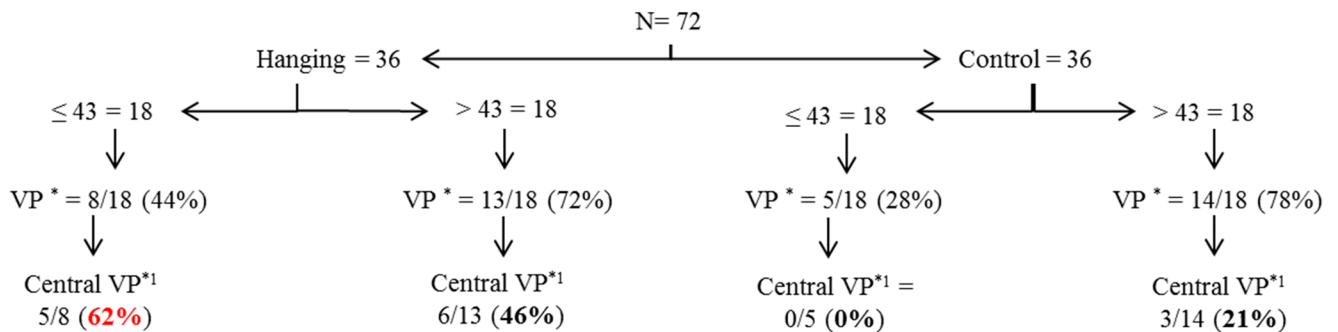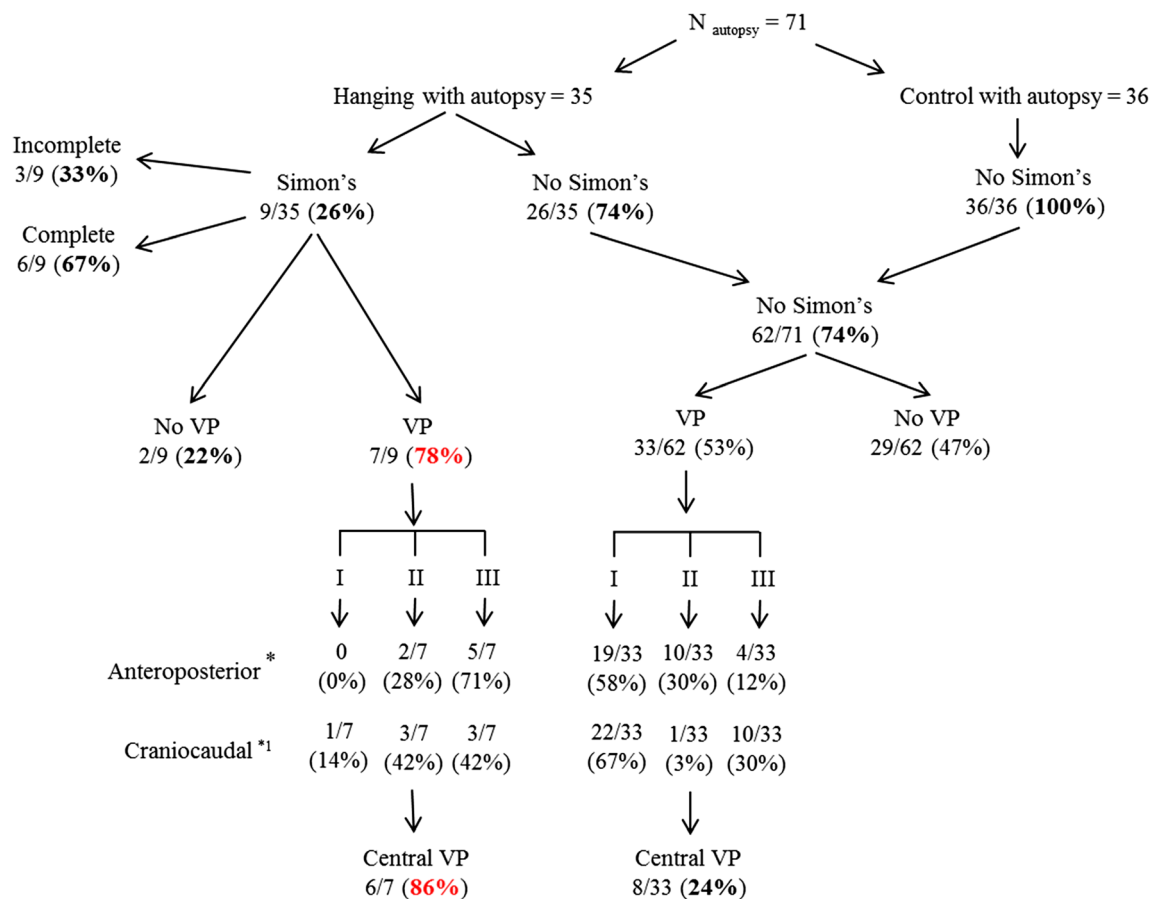

* Chi-Square Test not statistically significant

*[1] Chi-Square Test (p< 0.04)

Fig. 4 Overview diagram depicting the results regarding VP incidence and its localization categories with respect to hanging and control cases divided to age subgroups

Fig. 5 Overview diagram depicting the results regarding VP incidence and its localization categories with respect to presence of Simon's bleedings during autopsy:*, *[1]: Chi-Square test statistically significant (p < 0.05)

Combining both VP location within intervertebral disc and degenerative changes with result to the likelihood of hanging

Two parametric models (a GLM and a single layer neural net perceptron) were fitted to our data to examine the relationship between degenerative changes (DG index), the presence of VP located more centrally in the intervertebral discs ("Central VP") and the probability of that case being a hanging case (z-axis, Fig. 6d and e).

Both models similarly describe an increase of the probability of hanging when VP are present and located more centrally within one or more intervertebral discs (categories II and III for both anteroposterior and craniocaudal location, see also Fig. 6) and when degenerative changes are not prominent (GLM, whole model test, $p = 0.013$; effect test DG index not significant with $p = 0.08$, "Central VP" significant with $p = 0.008$; neural net single layer using hyperbolic tangent function: training RSME = 0.43, validation RSME = 0.46) (Fig. 6d and e).

The predicted likelihood of a hanging with the GLM is described with this equation:

$$p(Hanging) = \frac{1}{1 + e^{-(0.5563846397 - 0.277299995*DG\ index + 2.1022250773*VPcat2plus)}}$$

Correlate in macroscopy and microscopy

A correlate in one instance of an L4/L5 intervertebral disc central VP (a/p and c/c III localization, Fig. 8a) of a 62-year old female hanging case (degenerative changes of degree 2 for endplate

sclerosis, degree 1 for space narrowing and degree 2 for osteophytes on PMCT) showed tears in the native and subsequently formalin (4%) fixed specimen (Fig. 8b), whereas histology (Fig. 8c: HE stain) confirmed an avital nature of this finding (no erythrocytes; negative stain for Prussian Blue as indicator of no residuals of old hemorrhage or hemosiderin there).
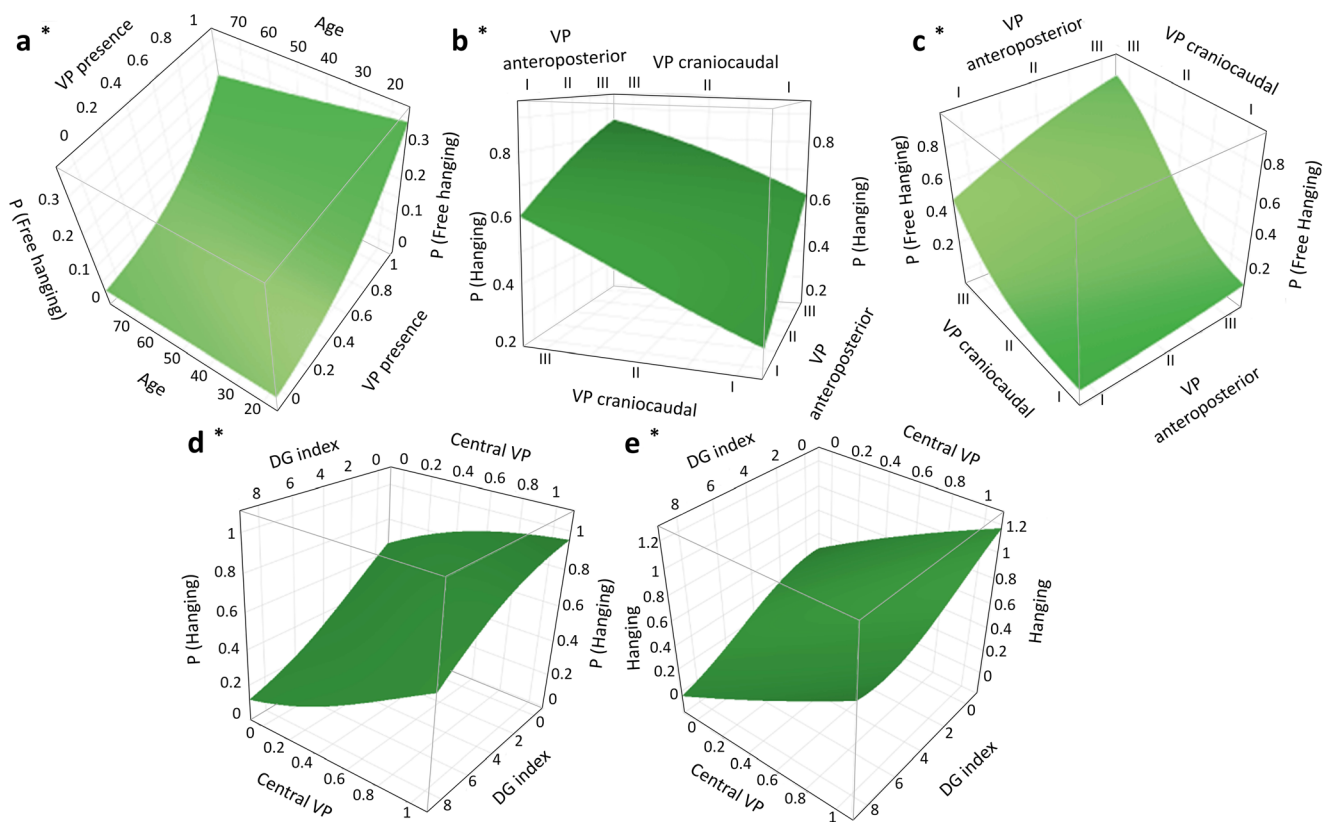
Fig. 6 Stars (*) denote whole model tests with statistical significance. – Generalized Linear Models (GLM) fitted to describe the probability of free hanging (a, c) and hanging (b). – **a*** Probability of free hanging can be shown to be a function of both presence of VP and age (whole model test with statistical significance). Thereby, presence of VP (scaled 0 to 1 here) increases the possibility of free hanging (z-axis) whereas increasing age mildly reduces this probability. This surface plot combines these results with a maximum probability of 35%. **b*** The VP location categories (I, II, III) (x-axis: VP craniocaudal location, y-axis: VP anteroposterior location) were used to describe the probability of hanging (both complete and incomplete) with a GLM. With increasing tendency for VP located in the center of an intervertebral disc, probability of hanging increases. Maximum probability of a hanging being present is ~85% with VP located centrally in both anteroposterior and craniocaudal axis. **c*** Free hanging can be described as function of VP location categories (I, II, III, x−/y-axes as in B) as well. Probability in this GLM also does not exceed ~85%. **d***, **e*** Data fitted using a GLM (**d***) and neural net (**e***) to predict probability of hanging based on the sum of all degenerative change scores (DG index) and a presence of more centrally located VP within one or more intervertebral discs. Both diagrams show a similar shape

Discussion

External forces that act on the spine also act on the intervertebral discs. With increasing age, these discs lose elasticity and lower forces may be required to produce tears.

In our data, complete hanging (contrary to incomplete hanging and non-hanging deaths) correlates with a high incidence of intervertebral VP on PMCT. In addition, increasing chronological age and the grade of degenerative changes of the spine correlated positively with the presence of VP on PMCT [19, 24–27]. With hanging, particularly with complete hanging, relatively high forces are incurred that correlate with the disruption and subsequent presence of central VP, even in the elastic discs of younger persons. In older persons, considerably lower forces, that may occur when turning or transporting a body, may be sufficient to produce VP in the aged, less elastic, and thus more brittle intervertebral discs.

The actual location of VP inside the intervertebral discs was shown to be relevant for attribution to higher external forces: only the more centrally located ("enclosed") VP were found to be typical for longitudinal extension of the spine, as centrally located VP correlated with hanging in general and especially with complete hanging, with statistical significance.

The presence of Simon's bleedings was significantly higher in the complete hanging group according to the results of the current study. Previous studies suggest that the genesis of these bleedings correlates with a higher drop in free suspension and violent rostrocaudal stimulation of the spine [4–6, 13, 17, 42–45]. Centrally located VP was significantly correlated with the presence of SB during autopsy.

Centrally located VP detected on PMCT is forensically relevant as an indicator for considering hanging as alternative cause of death, rather than proof of hanging. Based on our
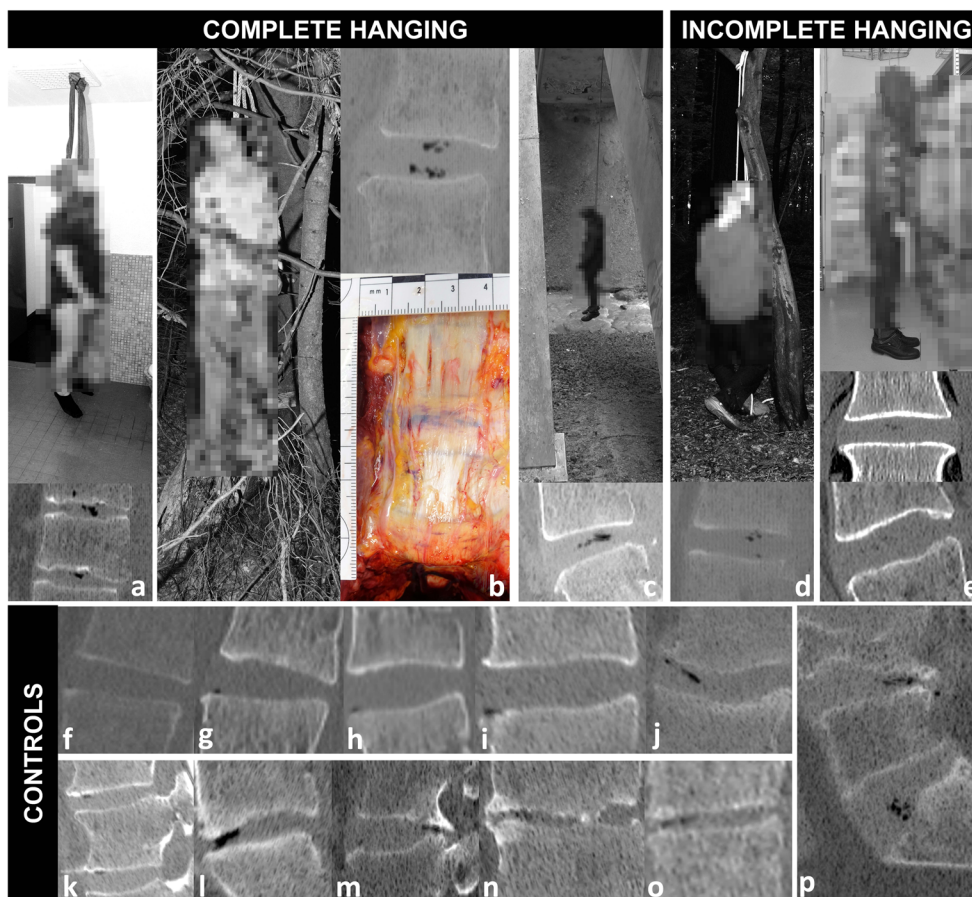
Fig. 7 Constellations of death scene and PMCT slices of the spine **a** Complete typical hanging of a 40 years old male and VP location a/p category III, c/c category III ("Central VP") with endplate sclerosis 2, space narrowing 2 and osteophytes 0. **b** Complete atypical hanging of 42 years old female, VP location a/p III and c/c II ("Central VP") with endplate sclerosis 2, space narrowing 1, osteophytes 2. Simon's bleedings were detected during autopsy. **c** Complete typical hanging under a bridge of a 25 years old male and VP location a/p category III, c/c category III ("Central VP") with endplate sclerosis degree 2, space narrowing 1 and osteophytes 0. **d** Incomplete atypical hanging of a 50 years old male, VP location a/p II and c/c III with degenerative changes degrees 0. **e** Incomplete atypical hanging, VP location a/p III and c/c II with degenerative changes degrees 0. **f–p** Controls with various degenerative changes degrees of the spine (increasing from f. to p.) and VP locations mostly adjacent to vertebral body plates (c/c category I-II) and in the anterior or posterior margins of the intervertebral discs (a/p categories I-II)

data, the statistical probability of central VP indicating a possible hanging case increases with decreasing age and with decreasing degree of degenerative changes of the spine. This is relevant in the wider context of identification of subtle

markers of possibly homicidal violence, which also has been identified as a relevant issue for forensic research [46].

The current study has limitations. Firstly, the study size is relatively small ($n = 36$ for both hanging and controls, $n = 18$

Table 4 Incidence of degenerative spinal changes and detection rates of VP on PMCT in the overall cases studied

	Endplate sclerosis [*1,4, 5]			Space narrowing [* 2, 5, 6]				Osteophytes [*3, 4, 6]			
Category	0	1	2	0	1	2	3	0	1	2	3
	27/72 (38%)	16/72 (22%)	29/72 (40%)	28/72 (39%)	29/72 (40%)	12/72 (17%)	3/72 (4%)	30/72 (42%)	20/72 (28%)	11/72 (15%)	11/72 (15%)
VP [*1, 2, 3]	8/27 (29%)	7/16 (43%)	25/29 (86%)	5/28 (17%)	21/29 (72%)	11/12 (91%)	3/3 (100%)	12/30 (40%)	8/20 (40%)	8/11 (81%)	11/11 (100%)

[*1, 2, 3] Chi-Square tests statistically significant ($p < 0.0001$)

[*4] Pearson's correlation ($r = 0.59$)

[*5] Pearson's correlation ($r = 0.76$)

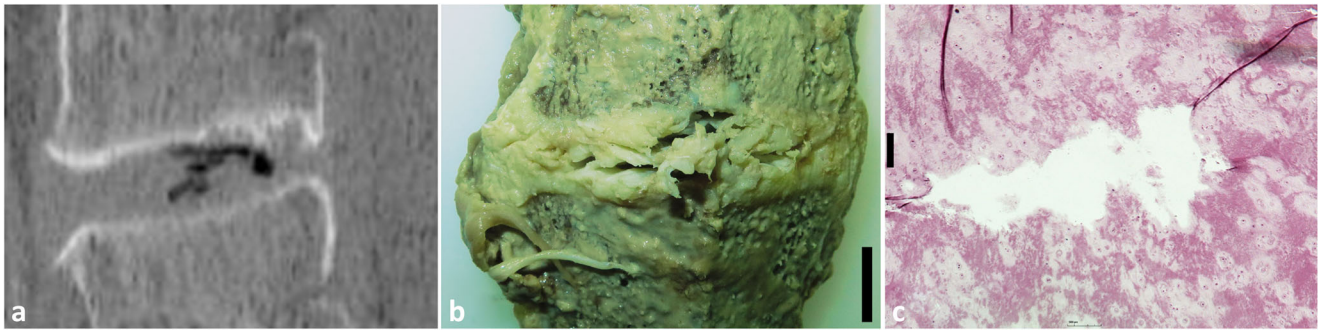[*6] Pearson's correlation ($r = 0.73$)

Fig. 8 **a** PMCT, **b** macroscopic (middle, bar 10 mm) and **c** microscopic (right, bar 500 μ, HE stain) appearance of tissue correlate in a case of hanging with VP located centrally in intervertebral disc

for each age group). Secondly, the time interval needed for VP to be developed and visible on PMCT is not known. Based on our experience, gas accumulations in the soft tissues, particularly smaller amounts, may appear relatively quickly in the postmortem period. Thirdly, as mentioned above, no evaluation of antemortem CT data was conducted for comparison. Fourthly, the current study was focused on the lower parts of the spine (thoracic and lumbar). Thus, neither neck findings (like muscular bleedings of the neck region, clavicles and cervical spine injuries), nor VP prevalence in the cervical spine on PMCT, were assessed. Further research that addresses these limitations may be needed.

Conclusion

Hanging as manner of death (especially free hanging) can play a role in the appearance of intervertebral discs gas accumulations (VP) in postmortem radiological results, especially in young decedents. Simon's bleedings, according to our results and previous research, are more likely to be evident in cases of complete hanging. However, PMCT as a supplementary tool to conventional autopsy cannot predict the presence of Simon's bleedings during autopsy.

Key points

1. Radiologically detected intervertebral disc vacuum phenomenon (VP) is caused by degenerative changes of the spine and trauma.
2. During hanging, particularly complete hanging, great loads and gravitational forces apply along the entire length of the spine.
3. A high incidence of centrally located VP within the thoracic and the lumbar discs is related to hanging, especially complete hanging, and the presence of Simon's bleedings.
4. Increasing age and degenerative changes of the spine correlate positively with the genesis of VP.

5. Centrally located VP can indicate that great loads may have affected the spine perimortem, especially in younger decedents when Simon's bleedings are also present.

Compliance with ethical standards

The authors of this manuscript declare no relationships with any companies, whose products or services may be related to the subject matter of the article.

Conflict of interest The authors declare that they have no conflict of interest.

Human and Animal Rights All procedures performed in studies involving human participants were in accordance with the ethical standards of the national research committee. This article does not contain any studies with animals performed by any of the authors.

Ethical approval Ethical approval was obtained by the Cantonal Ethics Committee of Zurich, Switzerland, Nr. 2015–0686.

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