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CASE REPORT

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An Unusual Case of Sudden Unexpected Death: Postmortem Investigation and Biomechanical Analysis of the Cervical Spine

ABSTRACT: A naked man died under peculiar circumstances and the postmortem examination revealed unexpected lesions in the cervical spine. Investigations of the cervical spine (computed tomography, magnetic resonance imaging, and histological examination) showed that a piece of bone was torn of the anterior part of vertebra C6 and that there was fresh bleeding in the surrounding tissue. The cause of death remained unclear but was most likely cardiac arrhythmia initiated by β-2 agonist inhalation due to an acute asthmatic attack. Data from biomechanical investigation using finite element analysis supported the conclusion that the cervical spine injury was secondary to impact during falling as a consequence of the cardiac arrhythmia.

KEYWORDS: forensic science, case report, sudden death, spinal fracture, finite element analysis, asthma, terbutaline, adrenergic β-agonists, metered dose inhalers, arrhythmia

Investigation of persons found dead in unexpected places and under unusual circumstances is a challenge to the medical examiner, who has to decide the cause and manner of death and the mechanisms of trauma. A medical examiner not able to attend the crime scene has to rely on information obtained from the forensic investigators and must take this into consideration when concluding upon the postmortem examination. In this case, a thorough examination of the cervical spine explained unexpected autopsy findings and added to the conclusion of the death circumstances.

Case Report

A 51-year-old man visited the house of a male acquaintance. The acquaintance, who was confined to a wheelchair, stated that the visitor had paid a social visit. Ten minutes after arrival, the visitor complained of sweating and uneasiness, inhaled a couple of times from a spray, took off all his clothes, and lurched to the hall where he collapsed. According to the acquaintance, the deceased knocked his head into a doorframe or a piece of furniture during the fall. Within 5 min, the acquaintance called for help and the arriving emergency doctor attempted resuscitation with no effect. There was no report of a seizure attack and the acquaintance denied a homosexual relationship with the deceased.

The deceased's family doctor stated that the deceased had been a healthy man suffering only from medically managed mild asthma treated with β-agonist and steroid inhalation combined with theophylline (tablet) and periodical migraine attacks, which had been treated with sumatriptan. A few months before his death, he had complained of chest pain; yet, an electrocardiogram and blood samples had shown no sign of heart disease. The deceased had no history of drug abuse or recent neck or head trauma and his car showed no sign of recent damage.

Investigations

Autopsy Findings

Examination of the body showed a slim, healthy-looking middle-aged male with a red bruise on the right eyebrow, two red bruises on the knees, and eight fresh superficial fissures around the anal opening. Around the genitals, anal region, femora, chin, and hands, a dried clear substance was noticed and the pubic hair had been shaved.

Evisceration revealed injury to the anterior part of the cervical spine at the C6–C7 level. The injury consisted of discrete localized bleeding in the prevertebral fascia associated with laceration of the anterior longitudinal ligament and the underlying superficial part of the intervertebral disk, and an avulsion fracture through the anterior–inferior corner of the vertebral body of C6 with a bony fragment partly detached from the vertebral body (Fig. 1). Examination of the internal organs showed slight general and coronary arteriosclerosis, and the lungs were moderately inflated.

The remaining morphological findings including macroscopic examination of the uncut, fresh brain were of no significance. Histological examination revealed moderate acute emphysema and bronchitis and slight interstitial fibrosis in the myocardium. The conduction system of the heart was examined according to standardized methods as described previously (1). No changes

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FIG. 1—*Anterior view of the cervical spine after removal of the esophagus. The prevertebral fascia and longus colli muscles have been scrabed aside. Arrows show blood extravasation around the prevertebral anterior longitudinal ligament.*

were found, except for slight fibrosis in the area around the sinus node, and the arteries were normal.

Toxicological analysis of the blood revealed no alcohol, drugs, or medications. Screening for theophylline (liquid chromatography with a diode array detector [Perkin Elmer, Wellesley, MA]), rohypnol (flunitrazepam) (gas chromatography with an electron capture detector [Hewlett Packard, Palo Alto, CA]), and cocaine and metabolites (RIA-assay) all turned out negative. No test was performed for γ hydroxy butyrate. The inhalation spray used by the deceased contained terbutaline—a short-acting, selective β-2 agonist often used in treatment of an acute asthma attack.

Genetic analysis of the dried clear material showed semen fluid without spermatozoa. In the secretions from the anal region, a few spermatozoa were demonstrated by microscopy, but further DNA analysis could not verify the presence of sperm.

Neuropathologic Findings

The brain weighed 1370 g and was moderately atrophic. There were two minor intact cerebral vascular malformations in the right frontal and left temporal lobe, respectively. The brain was slightly edematous with diffuse vascular lesions including fresh perivascular hemorrhages in the white matter, along the midline of the brain and the brain stem, as well as two minor bleedings in the leptomeninges.

Examination of the Cervical Spine

During autopsy, the spinal vertebral segments from C5 to Th1 (both included) were removed en bloc and examined with computed tomography (CT) scanning, magnetic resonance imaging (MRI), and conventional radiological examination, which showed a distinct irregular fracture line through the cortical margins of the anterior–inferior aspect of the vertebral body of C6 resembling a tear-drop fracture. MRI furthermore revealed a nonspecific increased signal in the C6–C7 disk and signs of laceration of the anterior part of intervertebral disk at C6–C7, as well as laceration of the anterior longitudinal ligament at the C6–C7 level. There was increased height of the C6–C7 intervertebral disk indicative of edema, although this could not be confidently verified on the MRI. No degenerative changes were identified on the diagnostic imaging examinations. Microscopic histological examination of the spine confirmed a linear fracture line through the anterior–inferior aspect of the vertebral body of C6 (Fig. 2). The adjacent anterior longitudinal ligament had suffered stretch injury with bleeding in the ruptured part. The intervertebral disk of C6–C7 showed histological evidence of acute internal disruption with fresh bleeding but no evident prolapsed disk. Histological examination of the spinal cord showed no sign of injury or bleeding, although discrete edema in the periphery could be identified.

Biomechanical Finite Element Analysis of the Cervical Spine

A biomechanical investigation was performed to determine whether a blow to the subject's head, sustained as a result of his falling, would be sufficient to cause a tear-drop fracture of the vertebral body of C6. The biomechanical analysis to answer this question consisted of two separate parts.

1. The mechanics of the fall and the determination of the magnitudes of the colliding force to the head and the force to C6.

The analysis was based on the mechanical laws of conservation of energy and momentum. In general, the fall direction during fainting is most likely to be toward the front (2). Based on the assumption that the first event interrupting the subject's fall was

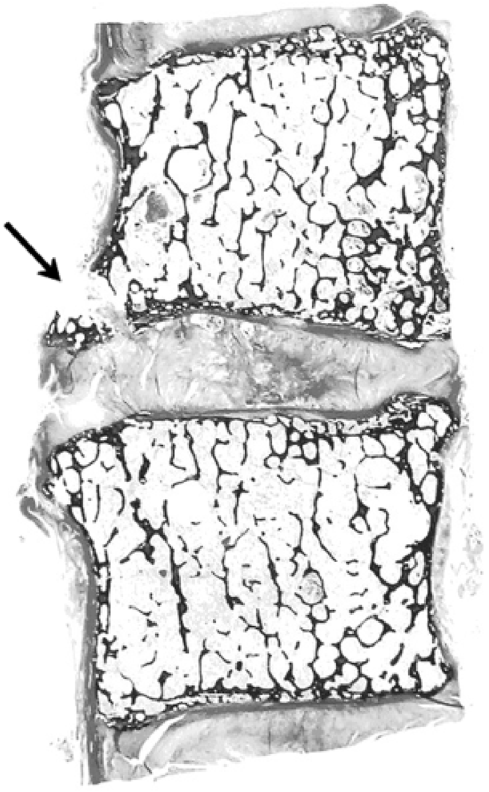

FIG. 2—*Saggital histological section of the tear-drop fracture in C6. The arrow indicates the fracture site. Note also disruption at the C6–C7 disk level.*

his head striking the doorframe, and that contact took place 1 m above the floor, the impact force to the head was calculated to be 2393 N for a conservative contact time of 10 msec at impact. The subsequent shearing force at C6 was also calculated and found to be 10,155 N (see Appendix A for details).

2. The finite element (FE) model and stress analysis of the vertebra C6.

A 3D FE model was made based on the actual CT scans of the cervical spine of the deceased. First, the individual scans were read into 3D visualization software Mimics 8.0 (Materialise, Leuven, Belgium), whereby the vertebra C6 was isolated from its surrounding tissues. On the reconstructed frontal and lateral views of the vertebra, the fractured segment became clearly visible (Fig. 3).

The number of small triangles describing the outside shape of the vertebra was too high to be handled directly by the FE program and therefore the number of triangles was reduced using a quadric-based simplification algorithm Q-Slim (3). After this reduction, the shape was imported into the COSMOS/M FE code (Structural Research & Analysis Corp., Los Angeles, CA) and meshed with 4-node tetrahedral elements, resulting in a model with 215,906 elements and 43,664 nodes. Material properties of the individual elements were assigned according to the gray values at their specific location in the original set of CT-scans using the method of Cattaneo et al (4). External loading consisted of the force acting on vertebra C6 as determined above, which was applied as a distributed load on the superior and inferior surfaces of the corpus. As a boundary condition, the movements of the nodes on the antero-inferior edge of the corpus were suppressed in the superior–inferior direction to simulate the presence of the anterior longitudinal ligament. Furthermore, the movements of the nodes on the articular surfaces of the lower facet joints were suppressed in the superior–inferior direction, simulating contact with vertebra C7. The actual analysis was performed in linear-elastic mode.

Due to the applied loading, the displacement of C6 could be described as an extension movement, with the anterior edge of the inferior surface of the corpus making an upward movement with respect to C7. In reality this movement would be counteracted by the anterior longitudinal ligament, but, if violent enough, damage to this region can well be anticipated.

The stress distribution during the impact showed high concentrations at the anterior surface of the corpus and on the pedicles of the vertebral arch (denoted by the red regions in Fig. 4). The magnitude of the stresses is such that the peak values already approximate the ultimate tensile strength of cortical bone, even here where the external force had been conservatively calculated. Since the cortical shell is significantly thinner at the anterior edge, a tear-drop fracture here is certainly not inconceivable.

Discussion

Traumatology

We have presented a case of cervical spine hyperextension trauma secondary to a fall. In this case, and in cases with similar trauma mechanisms, tensile loading of the anterior spinal structures such as the anterior longitudinal ligament and the intervertebral disk may occur in combination with compressive loading on the posterior elements of the cervical spine. Such a mechanism of trauma may cause laceration of the anterior aspect of the disk, separation of the disk from the cartilaginous end-plate of the underlying vertebral body ("rim lesions"), and avulsion fractures of the anterior aspect of the vertebral body and is frequently associated with injuries in the anterior spinal ligamentous structures (5–8). The compressive forces acting on the posterior elements may cause fractures of the spinous processes and the articular pillars as well as damage the cervical spine zygapophyseal joint structures including joint capsule lesions, contusion of the synovial folds, and fractures extending through the articular processes (9–11). Several autopsy studies have presented a high rate of occurrence of occult lesions to the intervertebral disk, including "rim lesions," contusions, and lacerations in people exposed to cervical spine hyperextension trauma (9–12).

Based on biomechanical principles and our knowledge of human anatomy and bone strength, it is possible to calculate the forces required to cause a fracture under the postulated circumstances. In this case, we have shown that the tear-drop fracture of C6 and damage to the surrounding soft tissues can well be explained from a dead-weight fall and subsequent collision of the head with a doorframe or a piece of furniture.

Cause of Death

The autopsy including histology revealed no significant organic disease except for slight myocardial fibrosis and an edematous brain with diffuse vascular lesions including fresh perivascular hemorrhages in the white matter, along the midline of the brain and the brain stem, as well as two minor bleedings in the leptomeninges. Both the neuropathological findings that are typical for mild cerebral contusion and the localized cervical spine injury to the intervertebral disk and anterior longitudinal ligament were in agreement with the finite element analysis, indicating that these injuries could have been sustained secondary to the head trauma during the fall at the moment of death.

Toxicological studies revealed no common drugs of abuse capable of causing sudden death. The one remaining reasonable

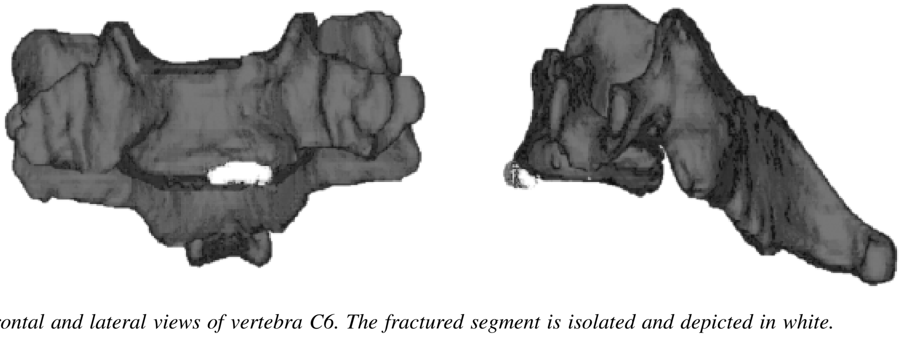

FIG. 3—*Reconstructed frontal and lateral views of vertebra C6. The fractured segment is isolated and depicted in white.*

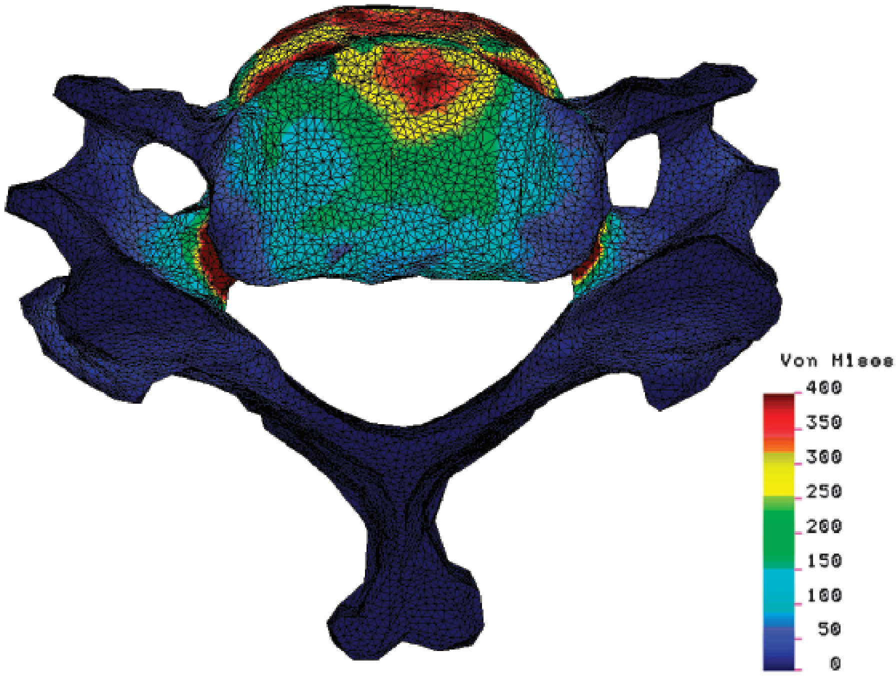

FIG. 4—*Caudal view of the distribution of the stress intensity (von Mises stresses; values in MPa) in vertebra C6 under the considered load case. Note the stress concentrations (red areas) at the pedicles of the vertebral arch and at the postero–lateral and anterior edges of the corpus.*

possibility is that death was caused by a malignant ventricular arrhythmia induced by the decedent's β-agonist medicament.

The safety of various β agonists in tablets, nebulizers, and metered-dose inhalers (MDI) has been questioned several times since the mini-epidemics of asthma deaths associated with isoproterenol use in the 1960s (13). It has been intensively discussed whether or not the use of MDI with selective short-acting β-2 agonists increases the risk of fatal and nonfatal cardiac events (14,15). A recent meta-analysis of the cardiovascular effects of β-agonists suggests that β agonists might lead to ventricular arrhythmias or ischemia, particularly if the heart is already weakened by arteriosclerosis and/or fibrosis. Also, the hypoxemia caused by respiratory distress and the hypokalemia induced by β-agonist inhalation might aggravate the potential cardiotoxity of the β agonists (16). Serious cardiac disturbances have been related to nebulized, oral, and intravenous β-agonist use but not significantly with MDI dispensers.

The relationship between asthma deaths and β-agonist MDI inhalation might be explained by an increased airway hyper-responsiveness caused by frequent and regular use, leading to a reduced response during an acute asthmatic attack (15,17), or the explanation may simply be that increasing use of bronchodilator medications is a marker of severe, poorly controlled asthma (17). However, if the latter were true, one would expect the autopsy to show hyperinflated lungs with air trapping as is found in typical asthma death.

Why the subject was found naked is not known. Sweating is a known but uncommon side effect from terbutaline use (18) and that effect rather than a premortem sexual event could be the explanation for his getting undressed.

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Appendix A

Based on the mechanical laws of conservation of energy and momentum, the mechanics of the fall and subsequent collision was calculated in order to estimate the magnitude of the colliding force to the head and the impact force to the cervical spine.

The deceased had the following anthropometric measures:

body length (l): 1.74 m;
body mass (m): 62 kg; and
body weight (W): 608 N.

If the witness description of the event is correct, it is reasonable to assume that the subject fell forward like a dead weight, with his body in an outstretched posture without any muscle contractions. Therefore, the position of the subject's center of mass can be taken to describe a circular trajectory during the fall, up to the instant that his head hits the doorframe. From conservation of energy, the following relationships hold as the subject's center of mass follows the circular trajectory before impact:

$$mgh_0 = mgh_\alpha + \frac{1}{2}J\omega^2 \qquad (1)$$

with g the gravity's acceleration (9.81 m/s^2), h_0 the height of the subject's center of mass, while standing straight, h_α the height of the subject's center of mass above floor level (dependent on α), α the angle describing the orientation of the body at an arbitrary point during its fall (0°: standing straight; 90°: laying flat on the floor), J the moment of inertia of the subject's body with respect to the axis of rotation at the level of the ankle joint, and ω the angular velocity of the body at orientation α during its fall.

Using anthropometric data (19), h_0 and J were calculated to be, respectively, 0.98 m and 66.5 kgm^2. The latter value was calculated by starting with the moment of inertia about a transverse axis through the subject's center of mass ($J_1 = mk^2 = 18.5$ kgm^2, with k, the radius of gyration, estimated to be about 31% of the body length) and using the parallel-axis theorem for shifting the reference axis from the body's center of mass to the level of the ankle joint ($J_2 = m(h_0 - 0.1)^2 = 48.0$ kgm^2). Substitution of these values and rearrangement of equation (1) yield the following expression for the angular velocity ω:

$$\omega = \sqrt{\frac{2mgh_0(1-\cos\alpha)}{J}} = \sqrt{18.54(1-\cos\alpha)} \qquad (2)$$

It was assumed that the subject's fall was taken to have first been interrupted by his head striking an object, such as a nearby piece of furniture or the doorframe, at a point 1 m above the floor. From this and geometrical considerations and our assumption regarding the nature of the body's initial trajectory, the impact to the head would have occurred when α equaled 55°. From the equations stated earlier, it follows that when impact occurred, ω equaled 2.8 rad/s or 160°/s.

With the assumption that the subject was totally relaxed—no muscle stiffening—as his center of mass followed the circular trajectory, the force to the forehead can be determined by treating the head and neck as a free body. This means that for the purposes of a conservation of momentum calculation, the head can be treated momentarily as if it were not attached to the body. It has an initial speed with respect to the room that is brought to zero within a time interval (Δt) by the force applied to it by the object it hits. From Newton's equations, the following relationship can be written:

$$m_h v_h = F\Delta t \qquad (3)$$

with m_h the mass of the head, v_h the head's speed at onset of impact, F the average force on forehead during impact, and Δt the duration of impact (often referred to as contact time).

Using the above-mentioned anthropometric data, m_h was estimated to be 5.1 kg. Based on the decedent's assumed mode of falling, the linear velocity of the head can be equated to the product of his body's angular velocity ω, calculated above and his body's length l. For the considered angle $\alpha = 55°$, the linear velocity of the head would then be 4.7 m/s. Contact times associated with fast human head strikes are usually found to be on the order of magnitude of milliseconds (ms) (20). To remain on the conservative side for an estimate, we opted for a Δt of 10 ms, which yielded a value of 2393 N for the force to the forehead.

For the estimation of the force to vertebra C6, the rest of the body was assumed to continue its fall in the fraction of a second after the impact to the head. However, as the neck stays behind, the angular motion of the trunk is suddenly cut short triggered by a moment at the neck (at the level of C6). Here, then, the law of conservation of angular momentum applies:

$$J_t\omega = M\Delta t \qquad (4)$$

with J_t the moment of inertia of the "headless" body with respect to an axis of rotation at the level of the ankle joint, ω the angular velocity of the "headless" body, M the moment at the neck on impact, this being equal to the distance from the neck to the ankle joint multiplied by the force to the neck, and Δt the duration of impact (often referred to as contact time).

Excluding the head and neck region from the previous calculation of the moment of inertia of the entire body yielded a modified J_t of 53.3 kgm^2. The angular velocity ω could be assumed to be instantaneously the same as calculated above. With a distance of 1.45 m from the neck to the ankle joint and again a conservative estimate for the contact time of 10 ms, this finally resulted in a force of 10,155 N to vertebra C6.