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Virtopsy–Postmortem Multislice Computed Tomography (MSCT) and Magnetic Resonance Imaging (MRI) in a Fatal Scuba Diving Incident

ABSTRACT: The body of a 44-year-old scuba diver was examined using postmortem multislice computed tomography (MSCT) and magnetic resonance imaging (MRI), and findings were verified by subsequent autopsy. The goal was to find out whether the important pathomorphological findings for the reconstruction of events and the identification of cause and manner of death could be identified using modern digital cross-sectioning techniques. The findings of a massive vital decompression with pulmonary barotrauma and lethal gas embolism were identified in the radiological images. MSCT and MRI were superior to autopsy in the demonstration of the extent and distribution of gas accumulation in intraparenchymal blood vessels of internal organs as well as in areas of the body inaccessible by standard autopsy.

KEYWORDS: forensic science, virtopsy, postmortem multisliced computed tomography, postmortem magnetic resonance imaging, forensic radiology, forensic autopsy, decompression sickness, barotrauma, gas embolism, scuba diving

Self-contained underwater breathing apparatus (SCUBA) diving is fascinating but not innocuous. The risks of hypothermia and drowning are combined with those of hyperbarism and change in ambient pressure (1). In general, severe injuries and fatal accidents are rare; minor accidents, however, frequently occur. It is estimated that three to nine deaths per 100,000 divers occur annually in the United States (2). In Germany, the number of severe diving accidents is estimated to reach 500 per year (3). According to the Swiss National Accident Insurance Agency (SUVA), 242 diving accidents occurred in 1999 in Switzerland (4). The Swiss Association for the Prevention of Diving Accidents (FTU) reports seven fatal diving accidents reported by the media in Switzerland in the 1999 (5). Since there is no official reporting system, the estimated number of unknown cases is believed to be high.

According to Bühlmann (6), heavy streaming and obstacles, exhaustion, hypothermia, mis-estimation and panic reactions, technical problems, a loss of consciousness due to a pre-existing medical condition, suicide, hyperoxia, and nitrogen narcosis may lead to drowning. Any of these causes may also lead to an urgent emersion with the well-known phenomenon of decompression sickness and death from fatal embolism of diving gas, pulmonary barotraumas, and/or death from extensive injury of vital organs.

The investigation of fatal diving incidents is a challenge for any forensic pathologist. Knowledge of complex pathophysiological processes and special forensic examination techniques are required (7,8). In order to provide useful information for the reconstruction of events and to determine cause and manner of death, the forensic autopsy should basically address the following questions:

- Are there signs of intravital dysbarism and/or decompression sickness with gas embolism?
- Is there any evidence of drowning?
- Was death caused by an external traumatic event?
- Is there any evidence of pre-existing medical problems that could have caused or precipitated the fatal outcome?
- Can any toxicological influence be excluded?

The autopsy diagnosis of vital decompression relies on the detection of venous gas embolism and soft tissue emphysema (1,6–8). Small amounts of gas within arterial blood vessels may be present in the form of "micro gas bubbles" due to decompression and passage through the intact pulmonary circulation. Arterial gas of greater extension, however, requires a right to left shunt through a persisting foramen ovale or pulmonary barotrauma (1,6). In order to differentiate a vital decompression from postmortem formation of gas bubbles ("off-gassing"), the following findings should be searched for: gas bubbles with cellular reactions, perivascular edema, parenchymal microhemorrhage, and, particularly, pulmonary fat embolism, to which a high evidential value is attributed (6,8,9). The technique for the demonstration of gaseous content in the heart by the emersion of gas bubbles in a pericardium previously filled with water or by the aspiration of gas with a syringe as described in many textbooks of forensic medicine is basically the same since the time of Richter (10–15). In some superficial blood vessels—like the meningeal veins and arteries and the coronary veins—the identification of gas bubbles is possible by special preparation techniques, but may be related to artifact (7,16,17). Gas

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accumulation in other regions of the body, however, are mostly hidden to the naked eye. An autopsy may thus be insufficient in detecting and demonstrating intravascular gas (18–20).

Pulmonary barotrauma can be proven by the presence of oxygen in embolized gas and the signs of lung trauma [pneumothorax, parenchymal hemorrhage, interstitial emphysema, rupture of alveolar walls (8)].

The idea to use modern digital cross-sectioning techniques, such as magnetic resonance imaging (MRI) and multislice computed tomography (MSCT) as a complementary tool in the investigation of fatal diving incidents is not new and has been proven to be of great value (8,18–21).

This is the first case of fatal barotrauma where autopsy findings are systematically compared to MRI and MSCT images. The goal was to find out whether the important pathomorphological findings could be identified in the radiological sections. The examination took place in the context of the Virtopsy Project (22–24).

Case History

A 44-year-old male scuba diver died shortly after a solo dive in great depth. He used a dry diving suit and breathed Trimix diving gas with a composition of 9.3% oxygen, 53.4% helium, and 33.9% nitrogen. According to witness statements, he literally spurted out of the water, making movements with his arms and rapidly losing consciousness. After being rescued by diving colleagues, he suffered a cardiopulmonary arrest. Resuscitation attempts were futile.

Analysis of the diving computer showed a diving depth of 100 to 125 m and a diving duration of 25 min. The diving gear was inspected by expert technicians and found to be functional.

No pre-existing medical problems were known.

Material and Methods

Postmortem Radiological Examinations Prior to Autopsy

A whole-body axial multislice computed tomography (MSCT) scan of the entire head and trunk was performed prior to autopsy on a GE Lightspeed QX/i unit with 4 × 1.25-mm collimation; 5 and 1.25-mm-thick sections were reconstructed; from the 1.25-mm axial sections, sagittal and coronal slices were reformatted. Magnetic resonance imaging (MRI) scans of the head, thorax, abdomen, and lower extremities were scanned in axial, sagittal, and coronal planes with T2-weighted (FSE: TR/TE 4000/90-98 ms) and T1-weighted sequences (FSE: TR/TE 400/14-20 ms) prior to autopsy on a GE 1.5 T Signa Echospeed Horizon, version 5.8 unit (General Electric Medical Systems, Milwaukee, WI). The slice thickness was 5 mm.

A board-certified radiologist analyzed the radiological data, and the results were compared to the autopsy findings. Postprocessing was done with an Advantage 4.0 workstation.

Forensic Autopsy

On the day following the radiological exams, a board-certified forensic pathologist performed forensic autopsy. The thoracic cavity was opened first, and the sternal bone was transected beneath the collarbones. These measures should prevent any opening of the vascular system before the heart could be examined. The heart was punctured using a disposable syringe equipped with a three-way valve (type discofix braun®). The aspirated gas was analyzed by gas chromatography using a Carlo Erba Mega-Series HRGC 5300 unit. Tissue specimens of all organs were collected under diatom-free conditions and analyzed by a biologist for the presence of diatoms (25). A histological exam of all major organs was performed. Lung tissue was collected by a double-blade knife and stained with sudan III for detection of fat embolism (26). Toxicological exams were carried out, including blood ethanol levels and immunological screening for common drugs and illegal substances.

Results

Brain and Skull

Autopsy Findings—After removing the dura mater, a great amount of gas bubbles was seen in the meningeal veins (Fig. 1*a*). These were attributed to venous gas embolism, since their quantity exceeded the artificial "gas bubbles" that can be seen after removing the dura (7). The brain tissue was edematous and showed disseminated grayish spots in the white matter. Marked perivascular plasma exudation with blood platelets and fresh perivascular hem-

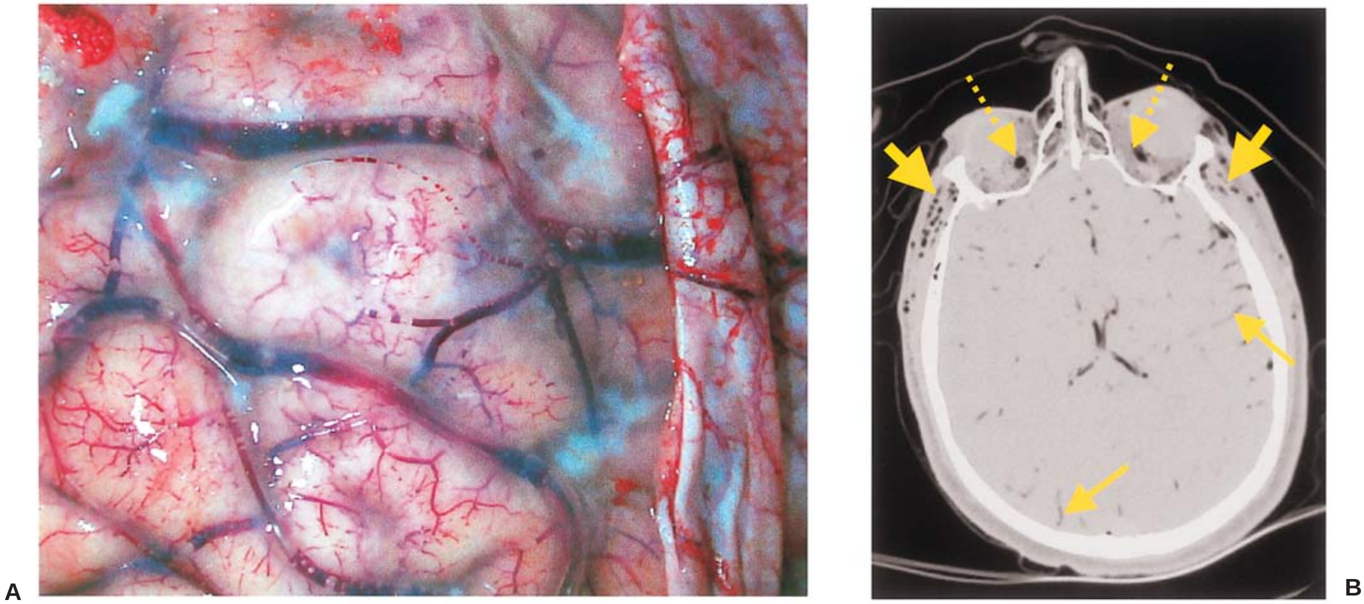


FIG. 1—(a) *Gas bubbles in meningeal veins, autopsy findings after removal of dura mater*; (b) *MSCT transverse section of the head demonstrates gas in brain vessels (thin arrows). Note gas accumulations in orbita (fragmented thin arrow) and subcuteaneous soft tissue (bold arrow).*

orrhage were observed in hematoxylin and eosin-stained histological sections of the brain.

Radiological Findings—In the MSCT and MRI sections of the skull, diffuse gas accumulations in intracerebral blood vessels were seen (Fig. 1*b*).

Cardiovascular System

Autopsy Findings—After opening of the pericardium, a tensely bloated heart was seen. Multiple gas bubbles were identifiable in the pericardial veins (Fig. 2*b*). The heart cavities were devoid of blood. Gaseous content was aspirated from the right and left ven-

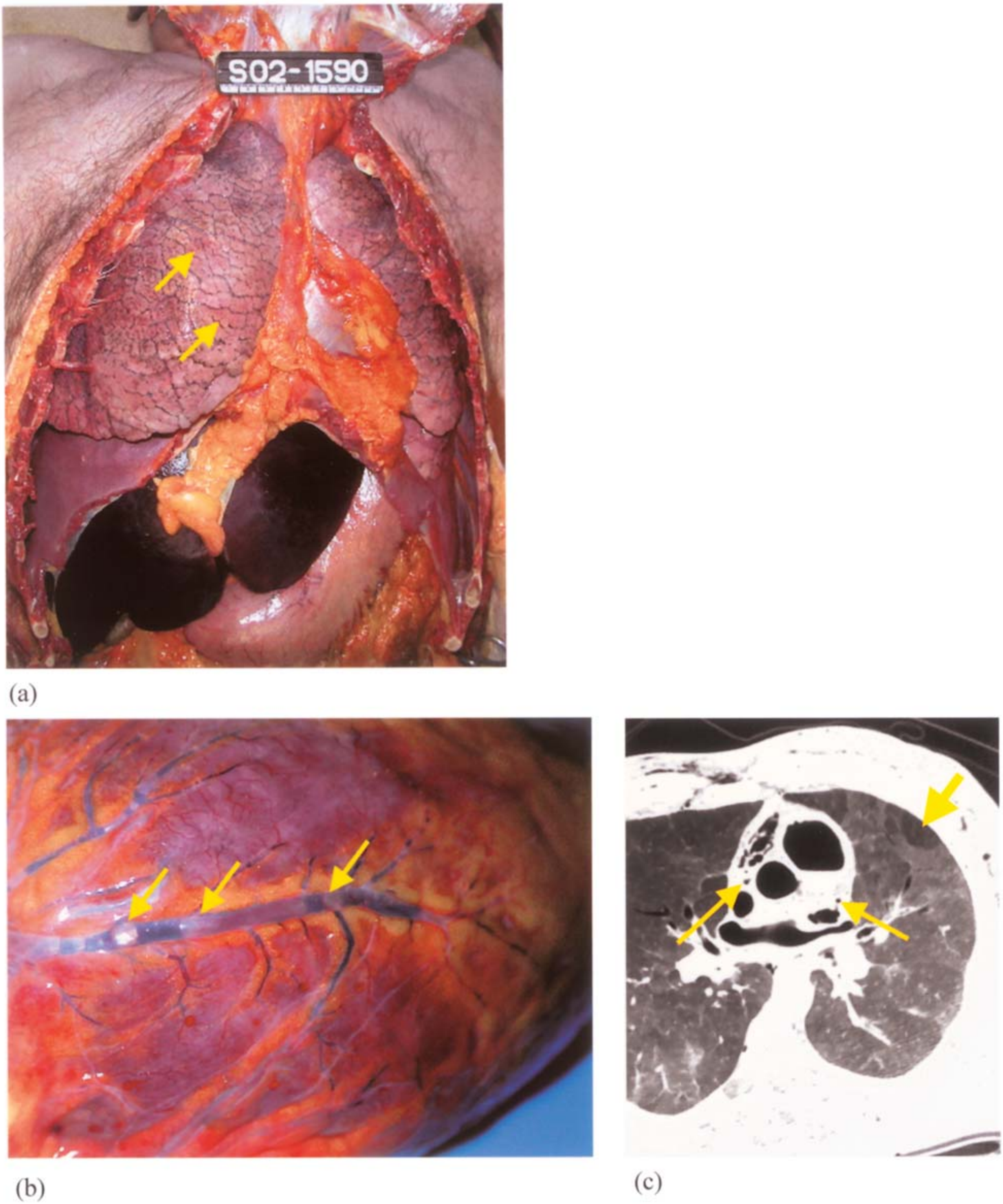


FIG. 2—(a) *Lung findings at autopsy. Note overinflation of the lung and Paltauf-like spots on pulmonary surface (arrows)*; (b) *gas bubbles in pericardial veins at autopsy (arrows)*; (c) *MSCT transverse section of the thorax demonstrates a mosaic pattern with overinflated secondary lobules (bold arrow) as well as gas in coronary vessels (thin arrows).*

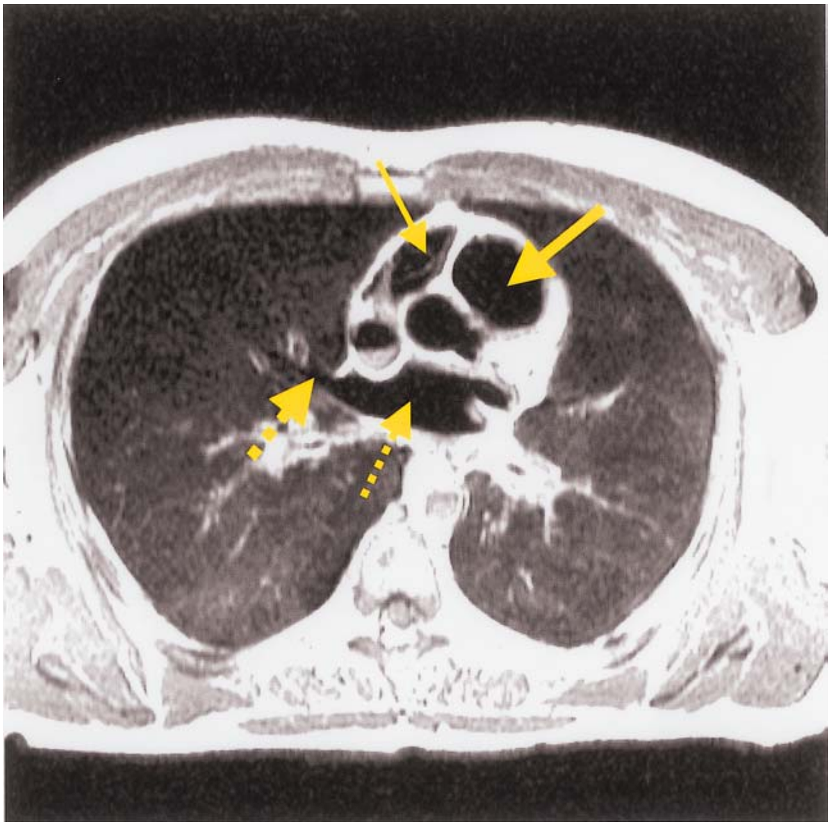


FIG. 3—*Gas distribution in the heart: MR T1 weighted transverse section of the thorax reveals gas accumulation in the right atrium (thin arrow), the right ventricle (bold arrow), and the left atrium (fragmented arrow). Note the heterogenous ground glass appearance of the lung parenchyma.*

tricles. The myocardial tissue was macroscopically unremarkable. The foramen ovale was closed. In the hematoxylin/eosin-stained histological sections of the heart, fresh patchy muscular necrosis was observed within the left ventricular wall.

Radiological Findings—The ascending aorta and the anterior part of the aortic arch and all heart cavities were devoid of blood and filled with gas (Fig. 3). The descending thoracic aorta and the superior vena cava contained partially sedimented blood. The left and right pulmonary arteries were filled with blood and showed no gas accumulations (Fig. 4). The pulmonary veins, however, contained gas in great amounts (see Fig. 3). Gas accumulation was also seen in the pericardial veins (Fig. 2*c*).

The abdominal aorta contained blood and was partially collapsed. The inferior vena cava was mostly free of gas and partially collapsed. Gas was also identified in the azygos vein, in the pelvic blood vessels, and in the splenic vein. Extensive gas accumulation was seen in the portal vein and the liver vessels (see Fig. 8).

Lungs

Autopsy Findings—The lungs were overinflated and showed irregular and poorly demarcated red blotches on the surface (Fig. 2*a*). The cut surface revealed a heterogenous picture of irregular patches of deep red congestion next to bright red dry areas. There was no pneumothorax and no fluid in the pleural cavities. The trachea contained gastric contents. In the hematoxylin/eosin histological sections, markedly distended alveolar spaces and ruptured alveolar

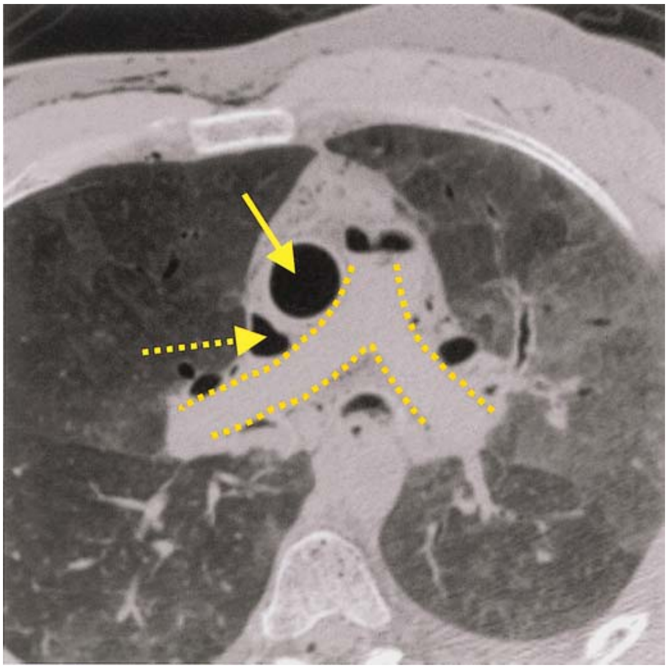


FIG. 4—*Gas distribution in the great thoracal blood vessels: MSCT transverse section of the thorax shows gas in the ascending aorta (thin arrow) and in the superior vena cava (fragmented arrow). The pulmonary trunk and main branches of the pulmonary arteries are filled with blood (dotted line).*

walls were seen as a consequence of acute overinflation, and marked pulmonary fat embolism was detected by the means of the double-knife technique [Grade III according to Falzi and Brinkmann (27)].

Radiological Findings—The cross sections of the lung were characterized by a mosaic pattern (air trapping) with emphysema in the secondary lobules, resulting in focal areas of abnormally decreased opacity next to areas of increased attenuation, a sign of diffuse interstitial and alveolar damage (pulmonary edema, hemorrhage). An upper lobe predominance or distribution was found (Fig. 2*c*, Fig. 3).

Abdominal Cavity and Abdominal Organs

Autopsy Findings—The abdomen was tensely bloated (see Fig. 6*a*). A great amount of gas escaped the abdominal cavity after opening. Apart from moderate congestion, all abdominal organs were completely unremarkable. Hemorrhagic tears and a stomach rupture were seen in the greater curvature of the cardiac region of the stomach (see Fig. 7*a*). The walls of the small intestine and colon showed irregular accumulations of submucosal blisters [pneumatosis intestinalis (Fig. 5*a*)]. The stomach and duodenum contained no watery fluid.

Radiological Findings—A massive gas accumulation in the peritoneal cavity (pneumoperitoneum) was easily identified on the abdominal cross-section imaging (Fig. 5*b*, Fig. 6*b*, Fig. 8). A discontinuation of the gastric wall was seen in the great curvature (Fig. 7*b*, Fig. 7*c*, Fig. 8). Gas bubbles were observed within the intestinal walls (pneumatosis intestinalis, Fig. 5*b*). The liver, spleen, and kidney showed extensive intravascular gas accumulations (Fig. 8).

Soft Tissue and Skeleton

Autopsy Findings—The external exam of the body showed no signs of injury apart from a dermal abrasion on the sternal area, resulting from resuscitation attempts (Fig. 6*a*). Severe emphysema of the soft tissues that covered almost the whole body surface was palpable. The penis and scrotum were inflated.

Radiological Findings—Gas inclusions were easily identified in the soft tissues of all examined body sections (Fig. 1*b*, Fig. 6*b*), the scrotum, and the cavernous bodies of the penis (Fig. 6*b*). Gas accumulations were obvious within the sternum (Fig. 6*b*), the vertebral bones (Fig. 6*b*), the spinal canal (Fig. 5*b*, Fig. 8), as well as in the hip joints and the subperitoneal area (Fig. 9).

Chemical and Toxicological Analysis

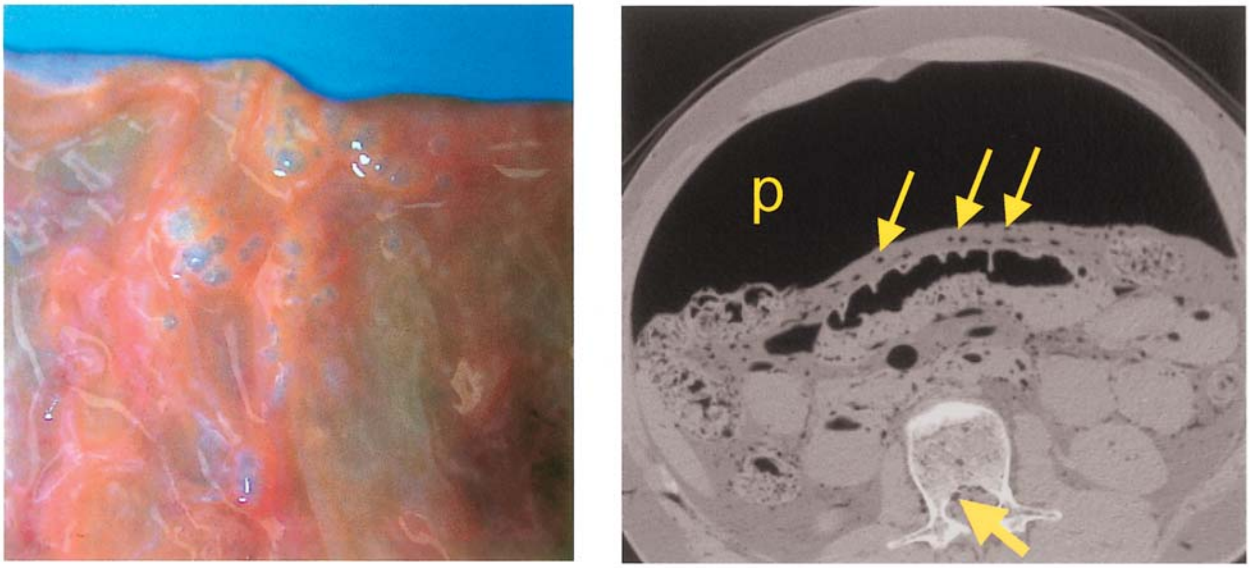
The gas collected from the abdominal cavity contained 32% helium, 52% oxygen, and 16% nitrogen. The gas from the right ventricle was composed of 31% helium, 39% oxygen, and 29% nitrogen, and from the left ventricle of 38% helium, 33% oxygen, and 20% nitrogen. No ethanol or drugs were found in blood or urine.

Discussion

Signs of Decompression and Barotrauma

In the case presented, perivascular edema, parenchymal microhemorrhage, and pulmonary fat embolism were identified, all vital signs for decompression. The vitality of decompression in the presented case was also inherently given by the gas distribution. The massive gas accumulation in the heart cavities as well as in the central blood vessels can only be explained by an intact circulation and gas embolism during emersion (19). A postmortem artifact by formation of putrefaction gas was excluded by a chemical analysis of gaseous content of the heart and the abdominal cavity. Barotrauma to the lungs was proved by the detection of high oxygen concentrations in the gas accumulations within the heart and abdomen.

MSCT and MRI were superior to autopsy in the demonstration of distributed gas collections in this case. Though the detection of gas in the heart and the superficial blood vessels of the brain and heart as well as that of soft tissue emphysema and of gas beneath



(a) (b)

FIG. 5—*Submucosal gas blisters (pneumatosis intestinalis):* (a) *at autopsy;* (b) *MSCT transverse section of the mid abdomen reveals gas accumulation in the bowel wall (thin arrows). Note massive pneumoperitoneum (p) and small gas bubbles in the epidural space of the lumbar spine (fat arrow).*

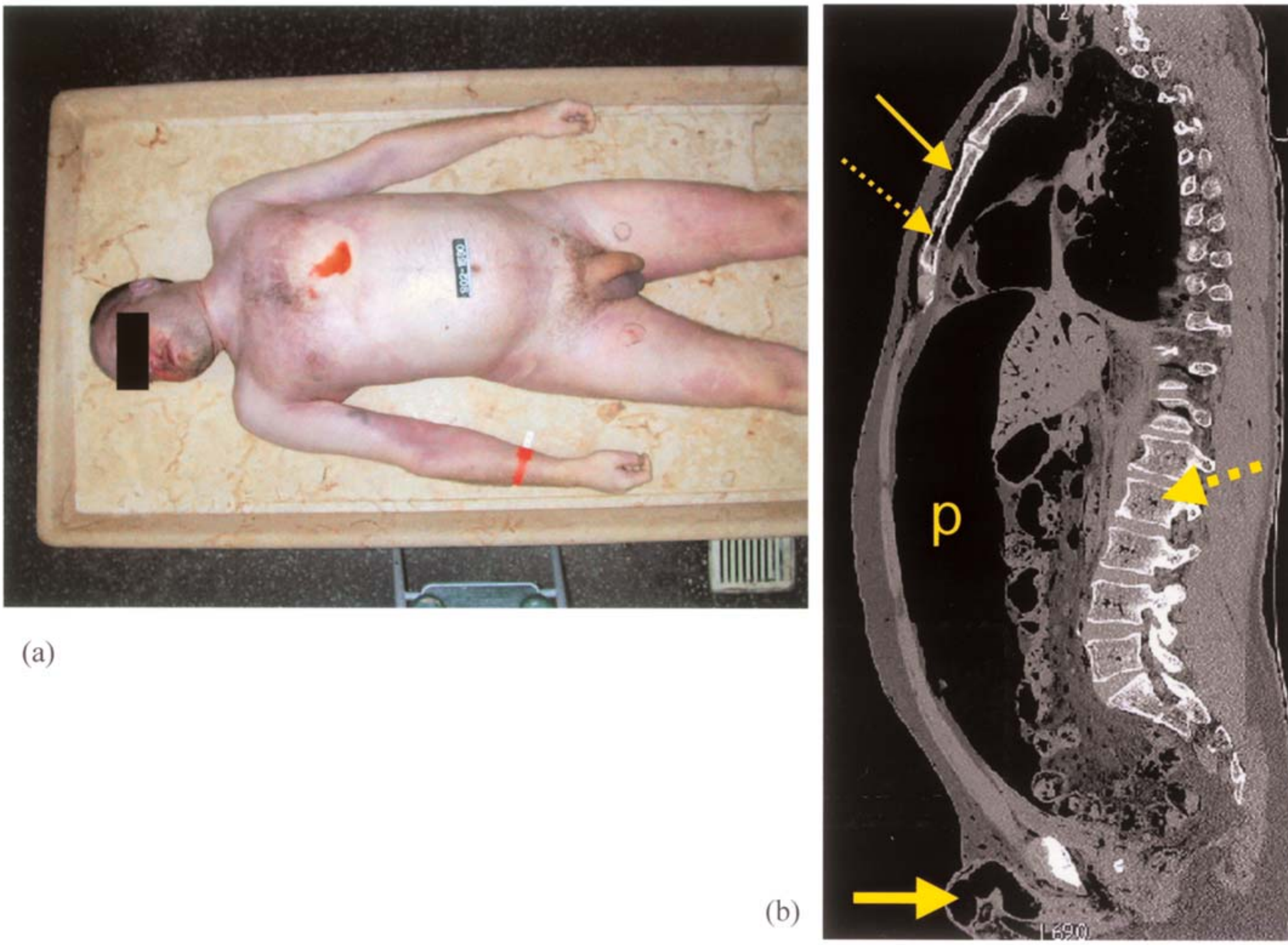


FIG. 6—*Pneumoperitoneum:* (a) *overview of the body before autopsy with massive bloating of the abdomen;* (b) *sagittal MSCT section (reconstructed image) demonstrates a massive pneumoperitoneum (p). Note the subcutaneous emphysema (thin arrow) as well as gas accumulations in bone marrow of sternal bone (fragmented thin arrow), vertebral bodies (fragmented fat arrow), scrotal area, and cavernous bodies of penis (fat arrow).*

the intestinal mucosa was unproblematic by standard autopsy techniques, the real extent and distribution of gas accumulations was assessed superiorly by the radiological cross sections. Gas within intraparenchymal blood vessels of the brain, liver, kidneys, and spleen as well as in remote areas of the body, such as the knee and hip joints and the spinal canal, were only detected on MSCT and MRI images.

Postmortem plain chest radiography has to be regarded as a valuable examination in scuba accident cases, since it is the best classical method of demonstrating gas embolism to the heart and central blood vessels (28). Compared to MRI and CT, it provides, however, no information on the exact distribution of gas within the thoracal and pulmonar vascular tree.

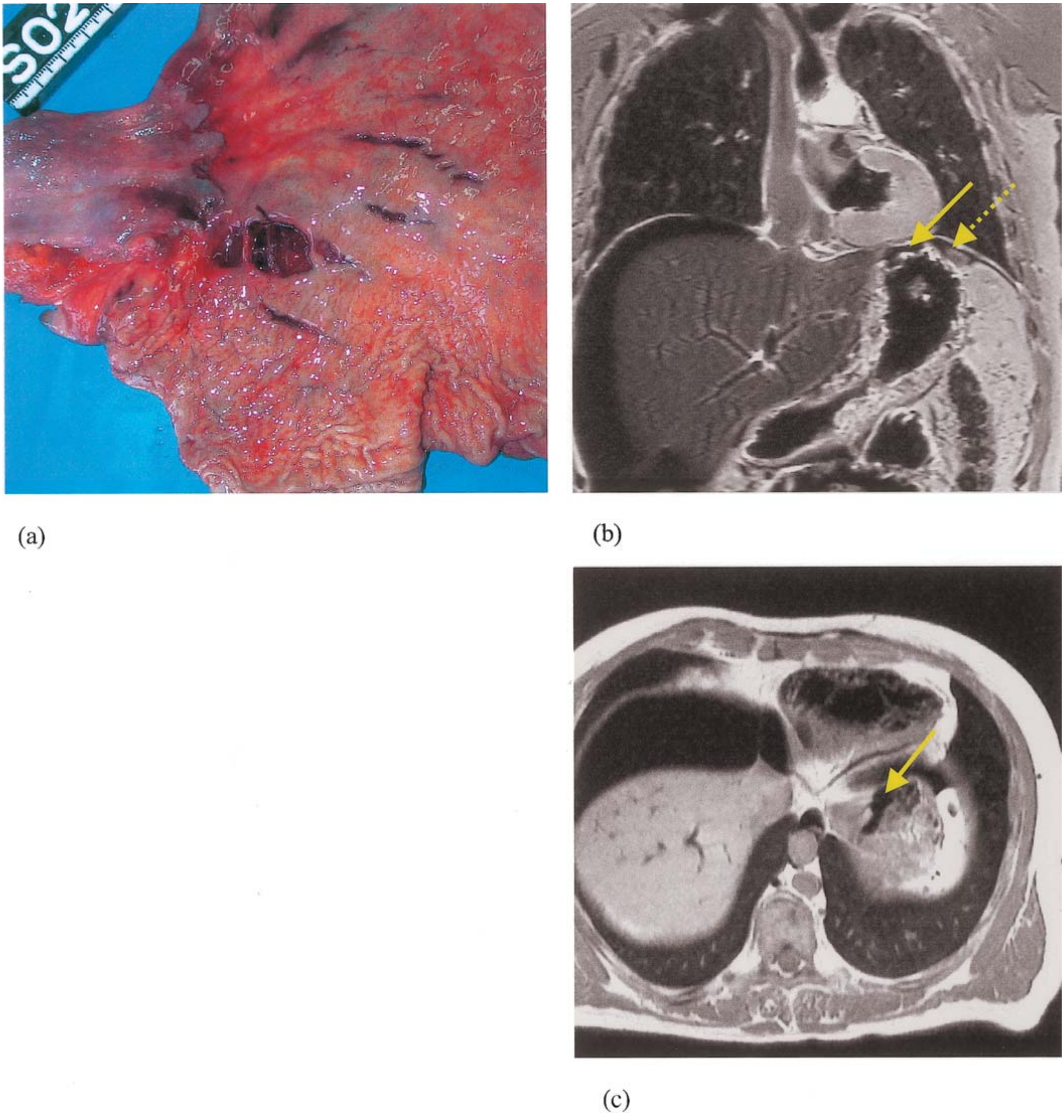
During emersion, gas may also be swallowed, leading to a rupture of the stomach as a rare finding in barotrauma (1,6,29). The gastric rupture in this case was detected radiologically by a discontinuation of the gastric wall on the MRI cross sections.

Signs of Drowning

At autopsy, as well as in the histologic examination, the lungs resembled drowning lungs in many aspects, such as overinflation, rupture of alveolar walls, and "Paltauf spots" on the surface. Drowning, however, was excluded by the absence of further autopsy signs of drowning, including froth in airways and water content in the stomach and intestines (11–15), and its absence was confirmed by a negative diatom analysis (25). By MSCT and MRI, the lungs showed a pattern that resembled the one described in two cases of drowning during the virtopsy project (23), although the mosaic pattern was much more heterogenous in this case compared to the two mentioned drowning cases. Based on the lung findings alone, it was thus not possible to differentiate between an overinflation of the lungs due to barotrauma and due to drowning (emphysema aquosum). Interestingly, the irregular and poorly demarcated red areas on the surface of the lung, which are one of the classic signs of drowning and referred to as "Paltauf spots"(11–15), were also documented in this case. This raises the discussion on whether "Paltauf spots" are a direct consequence of alveolar rupture rather than of hemolysis, as commonly assumed (15).

Traumatic Events, Pre-Existing Medical Problems, and Toxicological Influence

Consistent with the autopsy findings, no signs of a relevant pre-existing medical problem nor of external trauma were seen in the



(a) (b) (c)

FIG. 7—*Gastric rupture:* (a) *multiple hemorrhagic tears in gastric mucosa at autopsy;* (b) *coronal T2 weighted MR image; and* (c) *axial T1 weighted MR images reveal submucosal gastric tear with gas within the stomach wall [arrow in (b) and (c)] and gas accumulation under the left hemidiaphragm by pneumoperitoneum (fragmented arrow in (b)).*

radiological examination of the body. The influence of ethanol and commonly abused drugs was excluded by urine and blood analysis.

This is the first case of a lethal barotrauma that offers a systematic comparison between autopsy findings and modern digital cross-sectional imaging techniques. It shows that all initially asked questions could have been answered by the combination of MSCT and MRI and minimally invasive procedures (puncture of peripheral veins, abdominal cavity, heart cavities). It was proven that the diver didn't drown but died of massive embolism of diving gas as a consequence of pulmonary barotrauma and decompression sickness. There were no signs of an external traumatic event, toxicological influence, or a medical problem. A disfunction of the diving equipment was not found. The used Trimix gas contained an oxygen fraction of 9.3%. The gas accumulations collected from the body at autopsy showed, however, much higher oxygen fractions

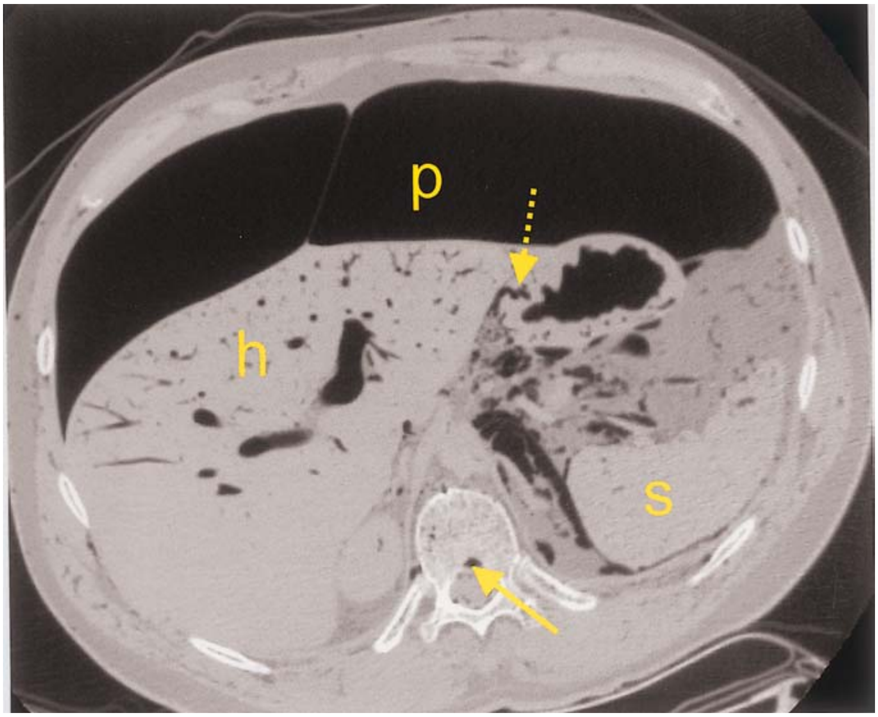


FIG. 8—*MSCT transverse section of the upper abdomen demonstrates a massive pneumoperitoneum (p) as well as gas accumulation in the branches of the portal and hepatic veins (h) and in the epidural space within the spinal canal (thin arrow). Note here the transmural extension of the stomac wall tear (fragmented arrow).*

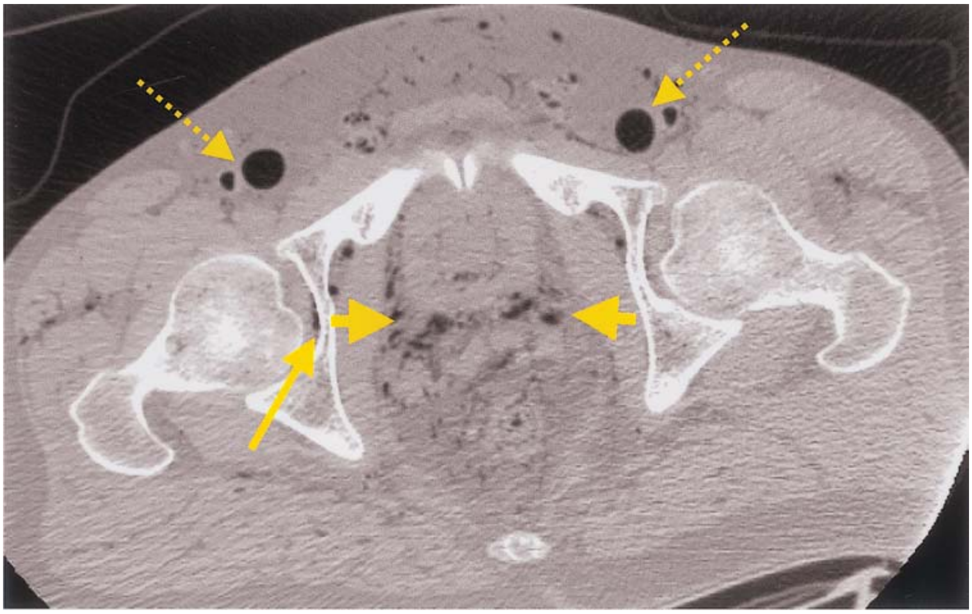


FIG. 9—*MSCT transverse section of the pelvis reveals gas accumulation within the right hip joint (arrow). Note again gas in the femoral vessels [artery and vein (dot arrows)] as well as in the subperitoneal area (bold arrows).*

(52% in abdominal cavity, 39% in right ventricle, and 33% in left ventricle). An oxygen accumulation in the tissue must therefore have occurred, which would suggest an oxygen toxicity as a possible reason for the accident.

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