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Pneumothorax during manned chamber operations: A summary of reported cases

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ABSTRACT

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In-chamber pneumothorax has complicated medically remote professional diving operations, submarine escape training, management of decompression illness, and hospital-based provision of hyperbaric oxygen therapy. Attempts to avoid thoracotomy by combination of high oxygen partial pressure breathing (the concept of inherent unsaturation) and greatly slowed rates of chamber decompression proved successful on several occasions. When this delicate balance designed to prevent the intrapleural gas volume from expanding faster than it contracts proved futile, chest drains were inserted. The presence of pneumothorax was misdiagnosed or missed altogether with disturbing frequency, resulting in wide-ranging clinical consequences. One patient succumbed before the chamber had been fully decompressed. Another was able to ambulate unaided from the chamber before being diagnosed and managed conventionally. In between these two extremes, patients experienced varying degrees of clinical compromise, from respiratory distress to cardiopulmonary arrest, with successful resuscitation.

Pneumothorax associated with manned chamber operations is commonly considered to develop while the patient is under pressure and manifests during ascent. However, published reports suggest that many were pre-existing prior to chamber entry. Risk factors included pulmonary barotrauma-induced cerebral arterial gas embolism, cardiopulmonary resuscitation, and medical or surgical procedures usually involving the lung. This latter category is of heightened importance to hyperbaric operations as an iatrogenically induced pneumothorax may take as long as 24 hours to be detected, perhaps long after a patient has been cleared for chamber exposure.

Keywords: chest tube; commercial diving; differential diagnosis; hyperbaric chamber; inherent unsaturation; nitrox; saturation decompression; submarine escape training; symptom presentation; tension pneumothorax; thoracotomy

CASE REPORTS

Case 1

In 1974, a 27-year-old commercial diver died secondary to undiagnosed tension pneumothorax during in-chamber decompression from an otherwise uneventful 492 fsw/150 msw transfer-under-pressure bounce dive [1,2]. It occurred aboard the SEDCO 135 F offshore platform operating within the UK sector of the North Sea. The diver first complained of chest pain at 90 fsw/27 msw. Modest chamber recompression (to 100 fsw/30 msw) resulted in prompt relief. The time frame involved in considering the complaint and proceeding as noted rendered his original decompression schedule inadequate. He was, therefore, committed to the only alternative option, namely, a greatly slowed saturation diving decom-

pression rate of ascent. Chest pain recurred at 80 fsw/24 msw. On this occasion, the diving supervisor considered it to represent decompression sickness (DCS), so ordered three atmospheres (99 fsw/30 msw) of recompression, again resulting in complete relief. Decompression was eventually resumed only for the same symptom to recur some 14 hours later while at 105 fsw/32 msw. The diver was again recompressed three atmospheres deeper. A shore-based senior diving supervisor considered this presentation more representative of pneumothorax and arranged for his company's contracted physician to accompany him to the platform. The physician entered the chamber and examined the diver at 80 fsw/24 msw and, despite the senior supervisor's protestations, diagnosed pneumonia and pleuritis. The physician departed the platform having started the diver on penicillin and analgesics. The fifth day of decompression was significant for steady clinical deterioration. An unsuccessful attempt was made to obtain a second medical opinion. The company physician was, therefore, encouraged to return to the platform. He reexamined the diver while at 36 fsw/11 msw, maintained his original diagnosis and departed. The diver suffered cardiac arrest five hours later and could not be resuscitated. An autopsy was significant for a left tension pneumothorax.

Case 2

Two years later, an offshore commercial diver working in the Norwegian Ekofisk sector of the North Sea complained of chest pain during decompression in a small deck decompression chamber (DDC) [3]. A Phillips Petroleum Company contracted physician was transferred by helicopter to the offshore structure, entered the chamber, examined the diver, and diagnosed a pneumothorax. Leaving instructions to maintain the chamber at its current depth, the physician returned ashore to recruit a radiographer and acquire a portable X-ray machine. For the first time, an X-ray image was obtained through a chamber's acrylic viewport, identifying a complete right pneumothorax (Figure 1). This same physician inserted a chest drain, and subsequent decompression proved uneventful, in stark contrast to the previous case.

Case 3

A commercial diving supervisor working in near zero visibility in the Gulf of Mexico suffered entrapment of his air supply umbilical, causing him to remove his helmet and rapidly ascend [4]. His surfacing was both dramatic and unexpected. He appeared to lose consciousness and began to sink. Upon recovery onto the support vessel, bloody frothy sputum was observed issuing from his mouth and nostrils, with no pulse nor spontaneous respiration evident. Cerebral arterial gas embolism (CAGE) was suspected, and immediate recompression to 165 fsw/50 msw brought about a rapid improvement. No information relating to any resuscitation efforts prior to and during recompression was reported. The diver was neurologically intact within 15 minutes, his residual complaints being chest pain and some respiratory distress. Left breath sounds were noted to be diminished. The diving company's shore-based medical control physician considered this representative of pneumothorax and advised that the diver undergo a slow linear decompression to 60 fsw/18

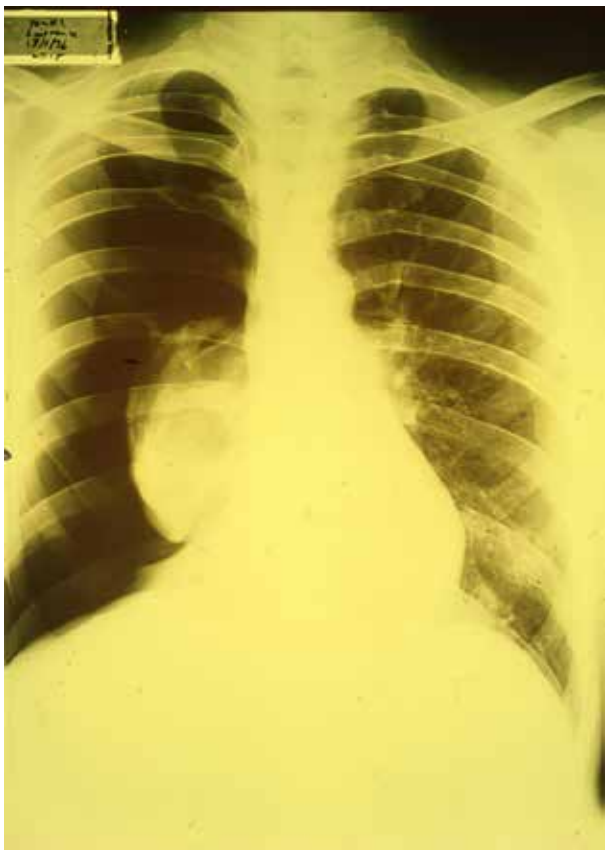

Figure 1. **Through chamber view port chest X-ray**

msw. Upon the diver's arrival at that depth, a second physician traveled to the accident site and entered the chamber. Breath sounds remained diminished below the level of the anterior clavicle but normal posteriorly. The diver was comfortable at rest, but deep inspiration caused left chest and back pain. A pneumothorax diagnosis was maintained. Greatly slowed decompression was reinstituted but with the diver breathing 100% oxygen as "frequently as possible." There was reluctance to insert a chest drain given the cramped, dimly lit, and unsanitary conditions (a "bacterial paradise" [4]) within the tight confines of this 42-inch/107-cm diameter DDC. Decompression was associated with subjective improvement, with breath sounds eventually equalizing. This represented the first reported case of pneumothorax in a pressurized diver treated medically, using inherent unsaturation alone. Central to the concept of inherent unsaturation is the "oxygen window" [5]. Metabolically, the production of 95% of the high energy phosphates that "run" the body relies on oxygen consumption. The myriad numbers of respiratory enzymatic chains in the mitochondria of the body's cells draw down dissolved gaseous oxygen to produce water and thereby maintain -5cm H_2O vacuum. The lung's lymphatic system pulls the produced water out of the pleural space. Provision of an enriched oxygen breathing mixture has, therefore, the potential to reduce a pneumothorax through metabolic consumption of oxygen at the pleural interface, thereby producing a "partial pressure vacancy" by way of the "oxygen window" to yield "inherent unsaturation."

Cases 4 through 8

Five other male commercial divers (age range 26-33) stricken with DCS suffered pneumothorax [6,7]. Each was treated by one of the authors (KVM) or a member of his medical group. After a trial of enhanced oxygen breathing and slowed decompression, life-threatening tension pneumothorax developed in all five. The respective diving contractor companies requested medical attendance, and in each case, a physician accompanied by a diver medic was flown offshore and entered the pressurized chamber. For the sake of brevity, only the first case is discussed, one that underwent thoracostomy with complications but achieved life-saving resolution of a tension pneumothorax and complete recovery of disabling DCS. This index case involved a 45-year-old working at 190 fsw/58 msw for 75 minutes. He returned directly to the surface to undergo "surface" decompression within a DDC. Upon eventual exit from the chamber, he complained of right upper quadrant abdominal pain and shortness of breath (SOB). Considered to represent manifestations of DCS, he was recompressed to 60 fsw/18 msw, where he subsequently developed visual distortion and hemiplegia. He was further recompressed to 165 fsw/50 msw. Hemiplegia and visual distortion resolved. Ascent began after 30 minutes, using U.S. Navy Treatment Table 6A [8]. Upon reaching 140 fsw/42 msw, SOB recurred, as did hemiplegia.

Return to 165 fsw/50 msw was associated with complete resolution. A supply of 60/40 nitrogen-oxygen (nitrox) mixture was delivered to the work site and the diver began breathing cycles of 20 minutes nitrox 20 minutes chamber atmosphere. At this point, a physician entered the chamber to find the diver with distended neck veins, SOB, and hyper-resonance over the right hemithorax. Tension pneumothorax was diagnosed, and the diver consented to thoracostomy. The anterior chest at the point of the right mid-clavicular line and second intercostal space was prepped with betadine and anesthetized with 1% plain lidocaine. A catheter over needle insertion followed. Bubbling of air through 5 mm of remaining lidocaine confirmed pleural space entry. Subsequent expulsion of the plunger out of the back of the syringe occurred without plunger traction and brought about immediate relief.

The clipped off finger of a sterile glove with a small nip in the fingertip was affixed to the hub of the catheter after the needle was removed, leaving the catheter in place. The catheter was then sutured in place. Ascent began after six hours at 165 fsw/50 msw using Royal Navy Treatment Table 71 [9], with the injured diver, physician, and diver medic breathing four 20-on/20-off cycles of nitrox every six hours. Nitrogen was admitted into the chamber to lower its oxygen partial pressure, and CO_2 was removed following the installation of lithium hydroxide "scrubber" [7].

At 115 fsw/35 msw, the diver accidentally pulled out the chest catheter and immediately became SOB. A French 20 chest tube was placed in the second intercostal space 2 cm laterally to the previous catheter site, and SOB again abated. Chest tube drainage was significant for empyema, which was sent for culture and sensitivity, and empiric IV antibiotics were started. In retrospect, the pitching of the diving support vessel in heavy seas likely caused the chest tube drainage system to back-flow through the tube into the pleural cavity. Subsequent ascent was conducted using a U.S. Navy air decompression table [8]. During the last 4 fsw/1.2 msw of ascent, inspissation of secretions in the chest tube from developing copious empyema had gradually occluded the tube. The diver re-tensioned, and a third chest tube was placed with the chamber now in an emergency department entrance driveway, where it had been transported during the lengthy decompression process. The diver was admitted to the ICU for management of his pulmonary infection and pulmonary oxygen toxicity. He recovered fully from his neurological DCS and acute respiratory distress syndrome (ARDS) and lived a healthy, unimpaired life.

Cases 9 through 12

The remaining four cases profited from the experience gained with the first case. They, too, suffered disabling DCS and were being managed on a standard oxygen treatment table when disabling tension pneumothorax developed despite a slow linear ascent. Each diver underwent an uneventful tube thoracotomy and experienced complete resolution of DCS. Strict adherence to a sterile approach, use of a Heimlich valve connected to the chest tube instead of water seal, and placement of the Heimlich 5-to-1 exit connector into the center of a Kerlix® roll secured with tape eliminated thoracostomy complications noted in the first diver.

Two cases of pulmonary barotrauma-induced pneumothorax, one bilateral, were reported secondary to a submarine escape training tank (SETT) at a Royal Navy facility in England [10]. Both trainees suffered loss of consciousness (LOC) upon surfacing and were immediately recompressed to 165 fsw/50 msw for presumed CAGE. One escapee convulsed prior to recompression and again upon arrival at treatment pressure. Subcutaneous emphysema was evident around his neck. During subsequent chamber decompression, abdominal breathing was observed, chest expansion remained symmetrical but with reduced inspiratory effort, and lung sounds were diminished bilaterally. Pneumothorax was diagnosed. In the absence of overt cardiovascular or respiratory distress, it was elected to continue decompression but at a greatly slowed rate rather than intervene surgically. This conservative approach was well tolerated, and upon arrival at surface pressure, the patient ambulated from the chamber. A chest X-ray was obtained and significant for bilateral pneumothoraces (70% right, 30% left). The second escapee likewise rapidly regained consciousness upon recompression. During chamber decompression, he complained of right upper abdominal pain at 140 fsw/42 msw and again at 100 fsw/30 msw. No other findings consistent with pneumothorax were evident until arrival at 60 fsw/18 msw, where a right pneumothorax was diagnosed per reduced breath sounds, hyperresonance with the absence of liver dullness, and decreased chest expansion. As the patient was not acutely distressed, decompression continued. At 30 fsw/9 msw, his condition deteriorated markedly. Full relief was achieved upon recompression to 40 fsw/12 msw. After some delay, it was elected to insert a chest drain, which allowed the remainder of the ascent to be accelerated without further complications.

Noting that "U.S. and U.K. SETT experience casts doubt on any general requirement for thoracentesis before decompression," these authors proposed a decision algorithm for in-chamber management of pneumothorax designed to avoid thoracotomy whenever possible [10]. We would add here that the addition of aggressive administration of 100% oxygen or appropriate "treatment mix" [8] would accelerate pleural air elimination and associated decompression.

A second incident at this facility involved a 21-year-old male submarine escape trainee [11]. Upon surfacing from a 30 fsw/9 msw SETT ascent, he complained of transient right-sided chest pain. A diving medical officer's examination proved unre-

markable. Upon exiting the water following a second ascent from the same depth, he appeared pale, unsteady, and complained of dizziness and diplopia. Immediate recompression to 165 fsw/50 msw soon resulted in full recovery. Decompression was uneventful until arrival at 30 fsw/9 msw, where he complained of right-sided chest pain. It was elected to continue his ascent. On examination upon exiting the chamber, a right pneumothorax was diagnosed clinically. This was confirmed by chest radiographs, and a chest drain was inserted. A repeat chest radiograph later that day showed the right lung re-expanded and revealed several well-defined cystic lesions of various sizes in the right mid and lower zones. Pre-morbid X-rays taken just days before the incident were initially reported as normal, but retrospective assessment showed distinct areas of low attenuation corresponding to the sites of some of the larger and subsequently demonstrated cysts. Computed tomography (CT) imaging was significant for several intrapulmonary cysts and subpleural blebs.

In another such case, a 25-year-old male Royal Navy SETT escapee surfaced with a loud gasp and lost consciousness [12]. He was recompressed as before, rapidly regained consciousness, and underwent a seemingly uneventful four-hour decompression. Upon exiting the chamber, he remained neurologically intact but with clinical features of a right pneumothorax and subcutaneous emphysema, observations missed during chamber ascent. Chest X-rays were significant for bilateral pneumothoraces, pneumomediastinum, subcutaneous emphysema, and several loculated gas pockets.

Other reports

Pneumothorax has also been described as a complication of clinical HBO_2 therapy. In 1968, the acrylic hull of an oxygen-filled single occupancy chamber catastrophically failed, resulting in explosive decompression from 66 fsw/20 msw [13]. The patient, who miraculously survived, suffered bilateral hemopneumothoraces.

While decompressing from her eighth hyperbaric oxygen treatment, a 55-year-old female complained of right upper abdominal pain at 10 fsw/3 msw [14]. Modest recompression to 15 fsw/5 msw brought about immediate relief. She was diagnosed with gastric distension, and decompression restarted at a slower rate. This was associated with increasing heart and respiratory rates and considered to represent anxiety. Upon discontinuing oxygen breathing during removal from the chamber, she became cyanotic, hypotensive, and briefly lost consciousness. During successful resuscitation, right breath sounds were absent, and left tracheal deviation was observed. A chest X-ray was significant for right lung collapse, depressed hemi-diaphragm, and mediastinal deviation. She was surgically managed, and her lung had fully re-expanded within eight hours. In terms of pneumothorax risk factors, her medical history included COPD, a permanent tracheostomy was in place, and she had struggled with mucus production during her previous hyperbaric treatments.

Three tension pneumothorax cases were reported from a single institution in 1991 [15]. All were female (age range 17 to 72) and had suffered acute severe carbon monoxide poisoning requiring on-scene CPR. Despite diminished breath sounds and subcutaneous emphysema being present in one patient while at pressure, pneumothorax remained undiagnosed in all three until the completion of chamber decompression. Each had probably entered the chamber with a pre-existing pneumothorax (potentially the result of rib fractures vs. pulmonary distention during resuscitation). As pre-hyperbaric treatment supine anteroposterior (AP) chest X-rays were uniformly negative, the authors suggested upright positioning is preferred. If not possible, as would have been the case with their patients, then a supine lateral view. These cases predated the introduction of point-of-care ultrasound.

A 13-year-old girl suffered carbon monoxide poisoning and subsequent drowning in a bathtub, leading to cardiac arrest [16]. She was resuscitated at the scene and transferred for HBO_2 therapy. On admission, she remained deeply unconscious, hypothermic, and had a Glasgow Coma Score of 3, with pupils non-reacting and maximally dilated. Her chest X-ray was significant for pulmonary edema, and her COHb was 48.7%. She arrested a second time. CPR was initiated and maintained during chamber compression. Spontaneous circulation returned, and HBO_2

therapy continued in the presence of severe ARDS. During her fourth chamber exposure, the hyperbaric team was advised that her pre-hyperbaric treatment X-ray was significant for a left- tension pneumothorax. Emergency decompression was attempted with predictable marked deterioration. She was immediately recompressed, and a chest drain was inserted. Subsequent decompression was uneventful. The patient eventually succumbed to her ARDS.

A 28-year-old male was rescued from a collapsed building 33 hours after an earthquake [17]. Twenty-one days later, he was referred for HBO_2 therapy in support of bilateral lower extremity crushing injuries status post decompression fasciotomies. He had also suffered acute renal failure, pulmonary thromboembolism, and ARDS, all secondary to prolonged entrapment. Having undergone six uneventful hyperbaric treatments, his seventh chamber decompression was complicated by sudden sharp right chest pain, dyspnea, tachycardia, and tachypnea. He rapidly deteriorated, lost consciousness, and suffered cardiopulmonary arrest. In-chamber resuscitation was initiated. Decreased chest wall movement and diminished breath sounds were noted over the right hemithorax, as was subcutaneous emphysema around his neck. Tension pneumothorax was diagnosed. It was elected to complete decompression as resuscitation continued, at which point needle decompression was performed but failed to generate anticipated relief. Chest CT confirmed tension pneumothorax, with complete collapse of the right lung and a left shift of the mediastinum. Insertion of a chest drain brought about an immediate return of spontaneous circulation.

In May 2023, a small steel dual-occupancy single-compartment air-filled chamber (www.classichyperbarics.com) installed in a private clinic in Utah, United States, suffered an acrylic viewport failure [18]. Uncontrolled decompression from 2.7 atmospheres absolute resulted in pneumothorax in the male patient and a perforated tympanic membrane in his wife, who had to accompany him. EMS transported both to a nearby emergency medicine facility for definitive care.

SUMMARY

Pneumothorax has complicated both operational diving and clinical hyperbaric activities, with case reports and small case series offering insights into its diagnostic challenges. Several examples of misdiagnosis were evident, as were instances where the diagnosis was missed altogether. Conventional wisdom holds that the injurious event occurs during chamber decompression secondary to pulmonary barotrauma. However, these reported cases, note that pneumothorax frequently pre-existed chamber entry and likewise was missed. This is somewhat difficult to reconcile as an untreated pneumothorax has long represented a contraindication to chamber exposure. It may have represented a failure to consider any need for such screening, screening inadequacies, low detection rates associated with X-rays for smaller areas of lung collapse, particularly involving anteroposterior views, or urgency to recompress serious forms of decompression illness, particularly involving medically remote settings.

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