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Tension pneumothorax in small odontocetes

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ABSTRACT: Pneumothorax, the accumulation of air in the pleural cavity, occurs when air enters the pleural space by the pleuro-cutaneous, pleuro-pulmonary, or pleuro-oesophageal-mediastinal route. Tension pneumothorax is an infrequent and severe form of pneumothorax where a positive pressure in the pleural space is built up during at least part of the respiratory cycle, with compression of both lungs and mediastinal vessels, and, if unilateral, with midline deviation towards the unaffected hemithorax. We describe 9 cases of tension pneumothorax in 3 species of small cetaceans (striped dolphin *Stenella coeruleoalba*, common dolphin *Delphinus delphis*, and common bottlenose dolphin *Tursiops truncatus*) from the western Mediterranean coast of Spain, and one case from a dolphinarium. Computed tomography (CT) imaging performed in 2 carcasses before necropsy showed lung compression, midline deviation, and pressure on the diaphragm, which was caudally displaced. Tension pneumothorax was recognized at necropsy by the presence of pressurized air in one of the hemithoraces. Seven of the pneumothorax cases were spontaneous (2 primary and 5 secondary to previous lung pathology). In the other 2 dolphins, the pneumothorax was traumatic, due to oesophageal-pleural perforation or rib fractures. We hypothesize that pneumothorax in dolphins is predominantly tensional because of their specific anatomical and physiological adaptations to marine life and the obligate exposure to extreme pressure changes as diving mammals.

KEY WORDS: Tension pneumothorax · Odontocete · Cetacean · Pulmonary bullae · Stranding

1. INTRODUCTION

Pneumothorax, the accumulation of air in the pleural cavity, occurs when air enters into the pleural space by the pleuro-cutaneous, pleuro-pulmonary, or pleuro-oesophageal-mediastinal route, and it is a common condition in humans and animals (Noppen & De Keukeleire 2008, Pawloski & Broaddus 2010). Depending on the cause, pneumothorax can be spontaneous (primary, if there is no previous respiratory disease, or secondary to other diseases and conditions), traumatic, or iatrogenic, and either unilateral or bilateral (Leigh-Smith & Harris 2005, Noppen & De Keukeleire 2008). Pulmonary blebs and bullae are

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causally related to spontaneous pneumothorax in dogs and humans (Noppen & De Keukeleire 2008), and bullous emphysema has been found in 26 out of 38 (68%) dogs with spontaneous pneumothorax (Puerto et al. 2002). Tension pneumothorax is a form of pneumothorax where affected individuals have a positive pressure in the pleural space during at least part of the respiratory cycle, with compression of both lungs and mediastinal vessels, and, if unilateral, with midline deviation towards the unaffected hemithorax (Leigh-Smith & Harris 2005). While simple spontaneous unilateral pneumothorax usually has a good prognosis, tension pneumothorax may be a life-threatening condition (Leigh-Smith & Harris 2005). Pneumothorax, often tensional, is a frequent and potentially fatal complication of mechanical ventilation in patients with acute respiratory distress syndrome (Woodside et al. 2003, Leigh-Smith & Harris 2005). In cases of tension pneumothorax, a 1-way pleural flap valve allows translocation of air from airways, alveolar tissue, and oesophageal or transthoracic perforations to the pleural space, but not its return, leading to an increase of interpleural pressure (Leigh-Smith & Harris 2005). This leads to forced progressive lung collapse (atelectasis), reduced pulmonary arterial perfusion and hypoxemia, and mediastinal deviation (Leigh-Smith & Harris 2005). Common clinical symptoms in awake, non-ventilated human patients with tension pneumothorax include chest pain, dyspnoea, shortness of breath, respiratory distress, tachypnoea, and hypoxia (Leigh-Smith & Harris 2005, Roberts et al. 2015).

Scuba divers are at increased risk for pulmonary barotrauma, which includes arterial gas embolism, mediastinal emphysema, or pneumothorax (Russi 1998), but such a risk has not been recognized in marine mammals, due to the assumption that apnoeic diving and evolutionary respiratory diving adaptations avoid barotrauma (Piscitelli et al. 2013, Fahlman et al. 2017). However, like terrestrial mammals, marine mammals may suffer pneumothorax unrelated to pulmonary overinflation, associated with other causes of pleural rupture or pleural cavity perforation. Accordingly, pneumothorax has been described in Florida manatees *Trichechus manatus latirostris* (Lightsey et al. 2006, Gerlach et al. 2013) and harbour seals *Phoca vitulina* (Akmajian et al. 2012). It is also listed as a finding in several reviews of causes of death in cetaceans (Zagzebski et al. 2006, Bechdel et al. 2009, Mazzariol et al. 2011, Díaz-Delgado et al. 2018, IJsseldijk et al. 2021), pinnipeds (Gerber et al. 1993, Brownlow et al. 2016), or sea otters *Enhydra lutris nereis* (Huckabone et al. 2015). A common bottlenose dolphin *Tursiops truncatus* suffered a pneumothorax following a stingray spine perforation (Weisbrod et al. 2020). Additionally, 8 cases of pneumothorax were described in striped dolphins *Stenella coeruleoalba* attacked by common bottlenose dolphins (Crespo-Picazo et al. 2021).

We describe 9 cases of tension pneumothorax in 3 species of small cetaceans, diagnosed by 2 different institutions, which were associated with pleural rupture or to oesophagus-mediastinal-pleural perforation and entry of air into the pleural cavity. As all of them were tension pneumothorax, we hypothesized that most, if not all, pneumothorax cases in cetaceans (at least in small odontocetes) will be tensional.

2. MATERIALS AND METHODS

2.1. Animals

Striped dolphins — Cases 1 to 5 and Cases 8 and 9 — were stranded at the Catalonian coast and were necropsied at the Veterinary School of the Universitat Autònoma de Barcelona (UAB), whereas Case 6, a common dolphin *Delphinus delphis*, was necropsied at the University of Valencia (see Table 1). The common bottlenose dolphin under human care (Case 7) was diagnosed and treated for tension pneumothorax by the veterinary team at the Oceanogràfic of Valencia for the first time in 2003 with some relapsing episodes in subsequent months. A map of the location of the animals is provided in Fig. S1 in the Supplement at www.int-res.com/articles/suppl/d155p043_supp/.

2.2. Diagnostic imaging

Computed tomography (CT) scans were performed before necropsy on 2 dead striped dolphins (Cases 4 and 5) at the UAB Veterinary Teaching Hospital, as a diagnostic aid, specifically searching for evidence of peracute underwater entrapment (PUE). The animals were secured in sternal recumbency, and images were acquired using a multidetector 16-slice helical CT scanner (Brivo CT-385, GE Healthcare). Non-contrast CT images including the head, thorax, and abdomen were obtained in soft tissue and lung windows. Technical parameters included soft tissue window (window width, WW: 350; window level, WL: 40) and lung window (WW: 1500; WL: 500), 120 kVp (kilovolt peak) to minimize beam hardening, automatically generated mA (range 15–16) and 1.25 mm slice thickness.

In the common bottlenose dolphin (Case 7), thoracic lateral and dorsoventral bilateral X-ray projections were taken at Oceanogràfic (Valencia, Spain) using a SPL-HF-VET portable X-ray unit (SedecalVet). Ultrasound examinations of both hemithoraces were performed using a portable ultrasound machine (Aloka SSD 500, Hitachi).

2.3. Pathology and ancillary investigations

Specimen preservation was scored from 1 (stranded alive) to 3 (moderately decomposed) (Kuiken & García-Hartmann 1991). The age of striped dolphins was estimated using body length and a Gompertz growth curve established for this species in the western Mediterranean (Calzada et al. 1997). Dolphins were necropsied according to established procedures (Pugliares et al. 2007, Cuvertoret-Sanz et al. 2020). Body condition was scored from 4 (robust, well nourished) to 1 (very thin) according to established criteria (Joblon et al. 2014). After 2012, in dolphins necropsied at UAB, blood was collected by heart puncture at arrival, before performing CT or necropsy, to obtain serum. In our standard necropsy procedure, the thoracic cavity is opened by the dolphin's left side, and before opening of the abdominal cavity. However, if pneumothorax was suspected or diagnosed prior to necropsy (based on lateral body asymmetry, thoracic percussion, or CT imaging) the thoracic cavity was opened from the unaffected body side. A complete set of tissue samples was fixed in 10% neutral buffered formalin and processed for histopathology in all animals except Case 7. Bacteriologic and mycologic investigations were performed as described in Cuvertoret-Sanz et al. (2020). Fisheries interactions and anthropogenic injuries were investigated following established criteria (Moore et al. 2013). After 2012, specific detection of CeMV (cetacean morbillivirus) and *Brucella* spp. were carried out as described in Soto et al. (2011) and Isidoro-Ayza et al. (2014).

3. RESULTS

Nine cases of tension pneumothorax in 3 delphinid species, including 7 cases in striped dolphins, 1 case in a common dolphin, and 1 case in a common bottlenose dolphin housed in an aquarium were identified. The presence or absence of pre-existing lung lesions connected to the pathophysiology of the pneumothorax was used to classify cases. Common findings in these animals are asymmetry of the thorax with unilateral distension, air hissing after puncture of the parietal pleura in the affected side, followed by chest collapse (Video S1; see videos in the Supplement at www.int-res.com/articles/suppl/d155p043_supp/), mediastinal deviation towards the unaffected side, and pulmonary atelectasis of the affected lung, that sank in formalin. Biometric data of dolphins included in this study are shown in Table 1. The carcass condition in our cases was fresh or incipiently autolytic, so post-mortem artifacts did not hamper assessment of pneumothorax. The main disease characteristics of our cases are summarized in Table 2. All animals tested negative for CeMV.

3.1. Tension pneumothorax with a prior lung lesion

A pre-existing lung lesion was identified as the source of the pleural rupture and pneumothorax in

Table 1. Biometric data of 9 cases of tension pneumothorax. All individuals were wild dolphins, except Case 7, that was held under managed care. TBL: total body length; BCS: body condition score. *Sc*: *Stenella coeruleoalba*; *Dd*: *Delphinus delphis*; *Tt*: *Tursiops truncatus.* A: stranded alive; D: dead stranded; NA: not applicable. M: male; F: female. ND: not done. Age was estimated by a growth curve established for striped dolphins in the western Mediterranean Sea (Calzada et al. 1997) and for common dolphins in the Irish Sea (Murphy & Rogan 2006)

Case no.	ID	Species	Stranding	Sex	TBL (cm)	Weight (kg)	BCS	Age (yr)
1	Cet-2/96	*Sc*	D	M	199	79	2	18
2	Cet-3/96	*Sc*	D	M	209	107	3	>26
3	N-567/12	*Sc*	D	M	175	67	3	5
4	N-28/21	*Sc*	D	M	206	85	2	>26
5	N-102/21	*Sc*	D	M	206	77	2	>26
6	Dd01.03.15	*Dd*	A	F	206	ND	2	>9
7	GAN: 25653324	*Tt*	NA	M	222	125	NA	12
8	B-11/11	*Sc*	D	F	194	80	3	15
9	N-29/15	*Sc*	A	M	204	89	2	>26

Table 2. Main pathological findings in cases of tension pneumothorax (see Table 1 for additional details)

ID	Lesions	Cause of death/ stranding	Laboratory data
Case 1 (CET 2/96)	Left-side tension pneumothorax with pre-existing bulla of 3 cm and a large fibrin clot near the bulla. Rough area on the pleural surface at the base of the bulla interpreted as a possible point of perforation. Granulomatous pleuritis in left hemithorax. Pulmonary atelectasis. Small lung nematodes present	Tension pneumothorax	*Aspergillus* sp. and *Penicillium* sp. *Aeromonas hydrophila* and *Pseudomonas* sp. in pleural cavity
Case 2 (CET 3/96)	Right-side tension pneumothorax. Pleural fissure (2 mm) at the pulmonary hilum, with a small subpleural bullae near the fissure. Mild purulent pleuritis. Pulmonary atelectasis. Small lungworms in airways	Tension pneumothorax	*Trueperella pyogenes* from pleural exudate
Case 3 (N-567/12)	Right-side tension pneumothorax with midline displacement to the left. Pleural perforation of 2 cm on the right lung, occluded by a fibrin clot, and communicating with large pulmonary cavities containing clotted blood. Lungworms inside this cavity, which had continuity with a large bronchus. Right lung atelectasis	Tension pneumothorax	Bacteriological investigation was not performed
Case 4 (N-28-21)	A CT scan was performed before necropsy, showing bilateral tension pneumothorax, more severe on the right side, as well as mild pneumopericardium. Loss of body condition. Chronic pyogranulomatous and necrotizing bronchopneumonia extending to and perforating the pleura, with intralesional gram-negative bacterial colonies. Transversal fracture of the mandible and the maxilla	Tension pneumothorax	*Psychrobacter phenylpyruvicus*, abundant colonies from pulmonary bulla and orifice
Case 5 (N-102-21)	A CT scan performed before necropsy showed a left-side tension pneumothorax with compression of the heart and mediastinum to the right side. A pulmonary bulla was discovered by inflation of the lung through a tracheal tube. The bulla expanded with inflation and collapsed when pressure was removed. No air leakage was observed. There were no histologic changes at the bulla, and the microbiological study of the lung was negative	Tension pneumothorax	No growth
Case 6 (Dd01.03.15)	Right-side tension pneumothorax. Perforation of the right lung and visceral pleura by a hook allocated at the oesophagus. Ulcers, cuts and abrasions in the oral and lingual mucosa secondary to line interaction	Hook and line entanglement. Tension pneumothorax led to euthanasia	Bacteriological investigation was not performed
Case 7 (GAN: 25653324)	Right tension pneumothorax. Rib fracture that lacerated the pulmonary pleura. Clinically, there was a non-audible normal vesicular murmur, non-visible visceral pleura/pleural space on ultrasound, and caudally displaced diaphragm. Increased buoyancy. Thoracocentesis and swimming restriction led to progressive improvement	Recovery from tension pneumothorax	Bacteriological investigation was not performed
Case 8 (B-11/11)	Left tension pneumothorax. Small punctiform orifice in the pleura of unknown cause, without bulla or trauma signs. Histologically, abundant lung nematodes	Tension pneumothorax	Bacteriological investigation was not performed
Case 9 (N-29/15)	Right tension pneumothorax. Histologically, mild parasitic pneumonia. No specific cause of the pneumothorax could be detected. Concomitant acute hepatitis caused by *Sarcocystis* sp.	Tension pneumothorax and acute hepatitis	Bacteriological investigation was not performed

Cases 1 to 5. A CT scan was performed in Cases 4 and 5 prior to necropsy.

In Case 1 the cause of death was a left-side tension pneumothorax, and it was diagnosed at necropsy when the pleural cavity was incised from the left.

The pleural cavity of the left hemithorax contained approximately 100 ml of a sero-haemorrhagic exudate, and the pleural surface showed a granulomatous pleuritis, with many white-yellow nodules from 2 to 5 mm in diameter, in both the parietal and visceral pleural surfaces. The compressed left lung had a superficial fibrin clot over a bulla 3 cm in diameter, located dorsally about 2 cm caudal to the tracheal bifurcation (Fig. 1). The inner surface of the bulla was covered by a yellow fibrous capsule. A rough area was present on the pleural surface at the base of the bulla, which was identified as a point of perforation. Low numbers of small lung nematodes (identified morphologically as *Skrjabinalius guevarai*) were observed on cut surface of both lungs.

Histologically, the irregular bulla surface corresponded to a perforation covered by fibrin, non-associated with additional lesions. A mild mixed inflammatory infiltrate was found in the lung near the limits of the bulla. The left pleura presented a chronic granulomatous and pyogranulomatous mycotic pleuritis with intralesional hyphae that did not extend to the lung. One of the diaphragmatic lymph nodes had a nematode larva within a discrete granuloma. The microbiological study grew *Aspergillus* sp. and *Penicillium* sp., as well as *Aeromonas hydrophila* and *Pseudomonas* sp, from the thoracic cavity (2001 European Cetacean Society Workshop; www.yumpu.com/en/document/view/10754430/tensional-pneumothorax-in-small-cetaceans). The primary origin of the bulla could not be determined.

Case 2 had a unilateral tension pneumothorax on the right thoracic side diagnosed at necropsy and determined as the cause of death. A 2 mm pinpoint perforation was present in the pleura at the pulmonary hilum behind the tracheal bifurcation with an associated small subpleural bullae. Discrete subpleural bullae were near the perforation. There was mild suppurative pleuritis of the right hemithorax, with dry yellow exudate over the dorsal mediastinum. *Trueperella pyogenes* was isolated from pleural exudate. Histopathologic examination did not reveal the cause of the fissure nor of the bullae.

Case 3 had unilateral tension pneumothorax on the right hemithorax, which was considered the cause of death. Gas bubbles were observed in mediastinal tissue. There was a 2 cm perforation of the pleura that was occluded by a fibrin clot (Fig. 2). The lung was fixed whole and serially sectioned following fixation. Underlying the pleural perforation there was an irregular 5 cm in diameter bulla which communicated with a larger 8 × 6 × 6 cm cavity in the pulmonary parenchyma, filled with clotted blood (Fig. 2), that communicated with a large bronchus. Inside this cavity there were small nematodes identified morphologically as *S. guevarai*. There was a small amount of clear red fluid in the trachea.

Case 4 showed asymmetry of the thorax, which prompted a CT scan prior to necropsy because of the suspicion of a tension pneumothorax that was determined as the cause of death (to consult complete CT scan see Supplementary file Video S2). CT study revealed a bilateral tension pneumothorax, more severe on the right side, as well as mild pneumopericardium (Fig. 3). In addition, 2 round mixed soft tissue/fluid attenuating masses (6.8 and 8.0 cm in diameter) with multiple small irregular gas-filled cavities were visu-

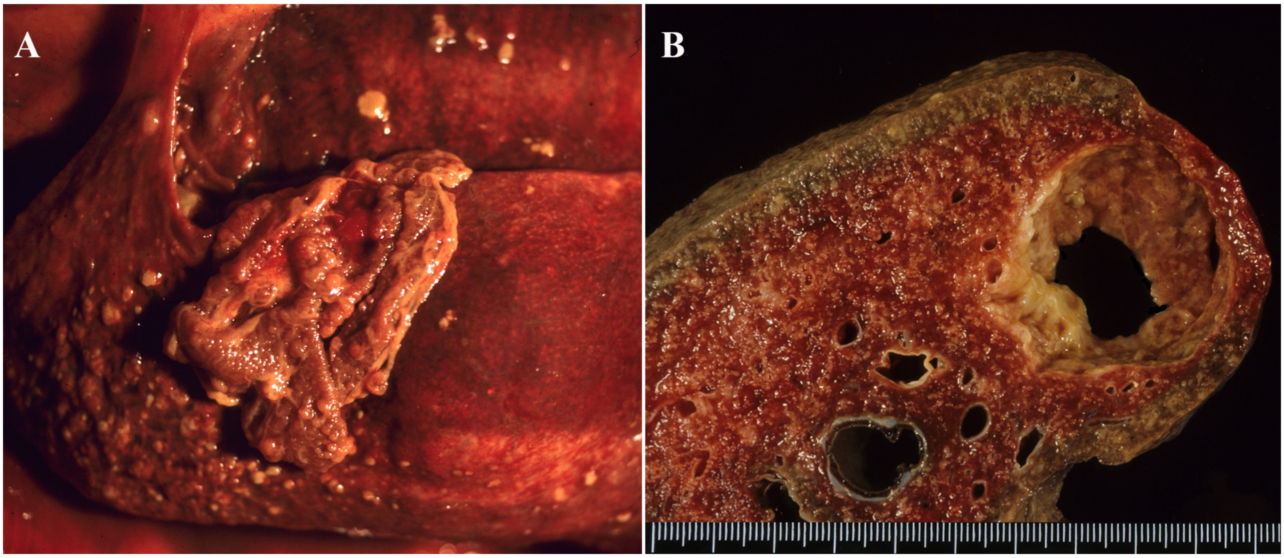

Fig. 1. Case 1 (Cet 2/96). Striped dolphin *Stenella coeruleoalba*. Left-side pneumothorax. (A) Lungs in place in the thoracic cavity. Mediastinum has been opened. A fibrin layer is found over the left lung, immediately over a lung bulla. Pleura shows a granulomatous mycotic pleuritis. (B) Sections of partially fixed left lung, showing a bulla of about 3 cm in diameter. The bulla had a pinpoint communication with the pleural space (not visible in the photograph). Scale is in cm (with mm divisions)

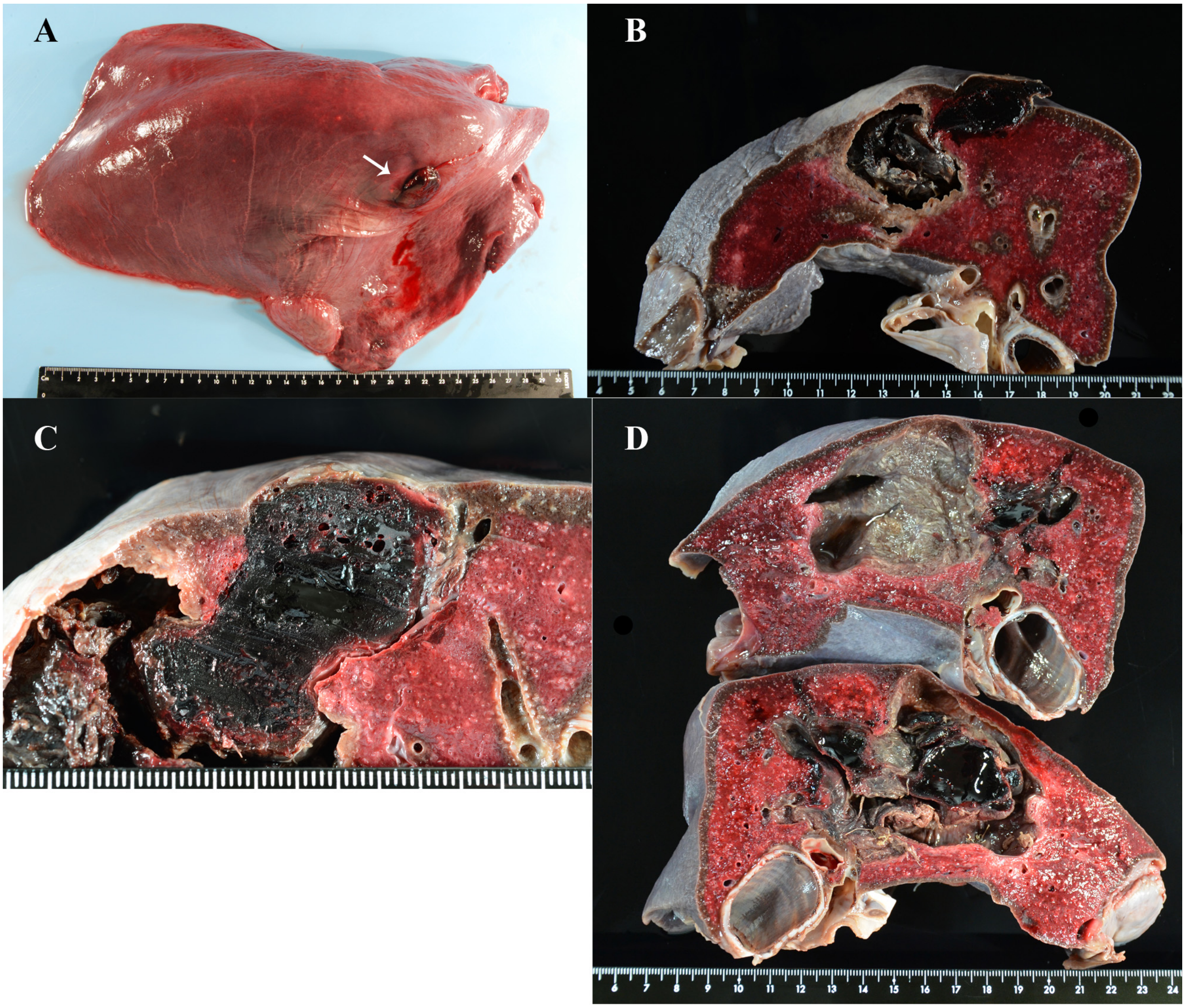

Fig. 2. Case 3 (N-567/12). Striped dolphin *Stenella coeruleoalba*. (A) Right lung, dorsal view. Craniodorsal aspect of the lung shows a pleural rupture of 2 cm with an associated blood clot of 1.5 cm in diameter (arrow). (B) Transverse section of right lung partially fixed in formalin. Ventrally to the blood clot there is a well-delimited cavity (bulla) within the lung parenchyma that contains clotted blood, communicating with the pleural fissure and associated with a larger, more irregular cavity. (C) Closer view of the communication between the bulla and the thin pleural fissure. (D) Halves of right lung tissue partially fixed in formalin, showing a large central irregular cavity of approximately 8 × 6 × 6 cm, and delimited by a fibrotic capsule. In the wall of the cavity there was a low number of small nematodes (*Skrjabinalius guevarai*)

alized in the cranioventral aspect of the right lung lobe. The caudodorsal aspect of the right lung had a rough wide pleural defect communicating the craniodorsal consolidated lung mass with the pleural cavity (Fig. 3). Before CT scan, a heart puncture was attempted in this dolphin, and the possibility cannot be excluded that this altered the existing lesions, creating pneumopericardium and/or extension of the pneumothorax to the left side.

At necropsy, the dolphin was moderately underweight with decreased blubber depth and had a transverse fracture of the mandible and the maxilla, as well as ulcerative lesions of the oral mucosa. The cranioventral right lung had multinodular to coalescing firm lesions filled with concentric layers of dense, white, caseous material associated with bronchiectasis. Caudally to these nodules there was a 2 cm in diameter defect in the pleura that connected to a large cavitary lesion filled with fibrin and necrotic debris (Fig. 3). The right diaphragmatic lymph nodes were markedly enlarged. Histopathological examination showed a severe, chronic pyogranulomatous

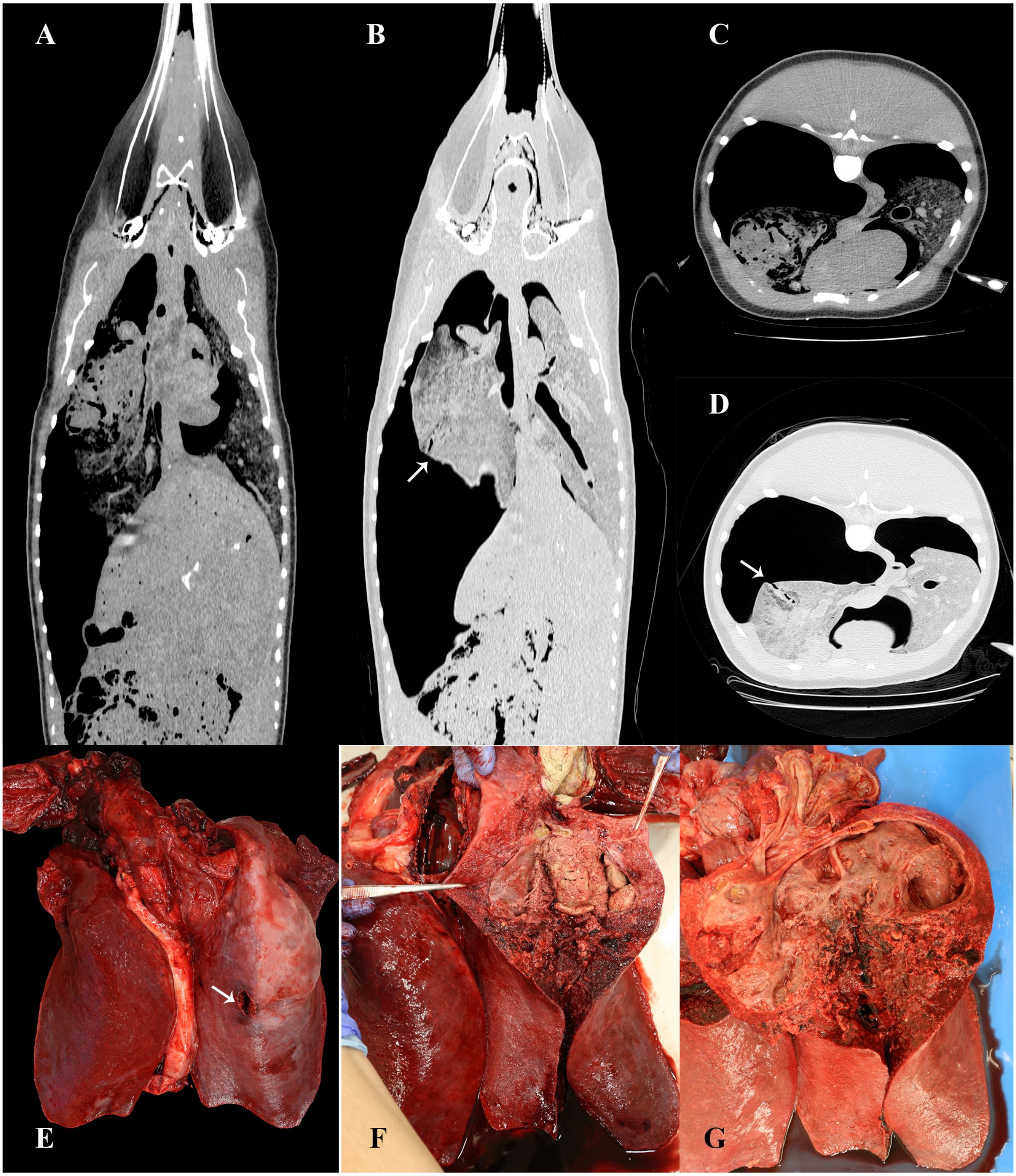

Fig. 3. Case 4 (N-28/21). Striped dolphin *Stenella coeruleoalba*. (A) Dorsal CT reconstruction in soft tissue window, showing a severe right-side tension pneumothorax, and pneumopericardium. Lung tissue in the cranial aspect of the right lung lobe shows an area of hyperattenuating parenchyma, with multifocal soft tissue hyperattenuating alveolar areas affecting the right lung lobe. The 2 round mixed soft tissue/fluid attenuating masses with gas content are visible. (B) Dorsal CT reconstruction in lung window, showing pleural rupture and communication of affected lung tissue with the pleural cavity (arrow). (C,D) Transverse CT image in (C) soft tissue window and (D) lung window demonstrating bilateral pneumothorax and pneumomediastinum. Affected lung tissue is hyperattenuating and shows one of the masses and a pleural rupture (arrow). In CT images, right of the dolphin is to the left of the image and left side of the dolphin is to the right of the image in both dorsal and transverse images. (E) Lungs, dorsal view. Right lung shows a prominent nodular lesion. Caudally, there is a focal pleural rupture 2 cm long surrounded by necrotic lung parenchyma (arrow). (F) Lungs, dorsal view, showing opened right lung lesion. Section shows that nodular lesions are 2 connected cavities filled by caseous-necrotic material. (G) Lungs, dorsal view after removal of necrotic debris and exposure of cavity walls

and necrotizing bronchopneumonia extending to and perforating the pleura, with degenerated neutrophils, macrophages, fibrin, cellular debris, and numerous cloud-like coccobacillary, gram-negative intralesional bacterial colonies. Culture results of the lesions in the right lung isolated abundant bacterial colonies of non-motile, gram-negative bacteria, identified as *Psychrobacter phenylpyruvicus.*

Case 5 had thoracic distention on the left side and a CT scan was performed before necropsy. A severe left-side tension pneumothorax, the cause of death, was visualized extending caudally until the 4th lumbar vertebra, compressing the left lung lobe and displacing the heart to the right (to consult complete CT scan see Video S3). The caudolateral aspect of the left lung lobe showed a focal curved indentation surrounded by a focal ill-defined soft tissue attenuating alveolar infiltrate (Fig. 4). At necropsy, the dolphin was moderately underweight with decreased blubber depth. The presence of tension pneumothorax was confirmed. Both lungs were removed with the trachea, the lungs were inflated through a tracheal tube and submerged in water, and no air leakage was observed. When pressurized, the depression observed in the lung surface at the CT scan expanded forming a 5 cm in diameter pulmonary bulla that collapsed again when air pressure was withdrawn (Fig. 4D). Histopathological examination revealed congestion of pulmonary parenchyma adjacent to the bulla, with fibrous tissue covering the bulla. No active inflammation was found in the lung. Aerobic bacterial culture did not grow any organisms.

3.2. Tension pneumothorax of traumatic origin

Case 6 was accidentally captured in a longline hook in the Valencia coast. The dolphin was found alive by divers, rescued from the fishing line and brought to port with 20 cm of line still present out of the mouth. The dolphin was assessed and triaged by veterinarians at the Fundación Oceanogràfic for stabilization. Due to evident distress, lack of vesicular murmur on right hemithorax, poor general condition and progressive deterioration, the animal was humanely euthanized. At necropsy, a tension pneumothorax was confirmed on the right hemithorax, associated with a perforation of the right lung and visceral pleura by a hook allocated at the end of the mid thoracic oesophagus (Fig. 5). This dolphin also had multiple small ulcers, cuts and abrasions in the oral and lingual mucosa secondary to line interaction.

Case 7 was held in the facility of the Oceanogràfic of Valencia. It presented with a rib fracture and tension pneumothorax on the right hemithorax in 2003, at an approximate age of 12 yr. Normal vesicular murmur was not audible in the affected hemithorax. On transthoracic ultrasound visceral pleura/pleural space were neither visible. A collapsed right lung was confirmed on radiography as well as a broken rib that most probably lacerated the pulmonary pleura (Fig. 6). The diaphragm was displaced caudally due to overpressure. The dolphin was reluctant to dive, showing an abnormal, increased buoyancy. All these radiographic and clinical signs are diagnostic keys to detect *in vivo* cases of pneumothorax. A conservative treatment was proposed, but due to progressive deterioration of the clinical condition during the following days, an ultrasound-guided thoracocentesis was practised to evacuate all accumulated pressurized gas and provide lung expansion, as confirmed on radiographs, ultrasound and auscultation. The dolphin was restricted in swimming activity and diving depth capabilities during several weeks with improvement, but its condition partially relapsed (just with some gas observed in the pleural space but not full tension pneumothorax) on 2 occasions after exercise and re-established diving activity in the 10.5 m deep pools. The dolphin fully recovered around 1 yr after the incident with periods of restricted dive depth. Bone remodelling/encapsulation of the broken rib edge and pleural healing mitigated further lung damage and pneumothorax in case of diving/exercising. The dolphin was clinically normal for the subsequent 11 yr at the facility, and in 2014 he was transferred to another dolphinarium, where he died in 2016 from an unrelated cause.

3.3. Tension pneumothorax without a pre-existing lung lesion

Case 8 had a left-sided tension pneumothorax that was considered the cause of the stranding. The left lung had a small punctiform orifice in the pleura in the dorsal hilar portion of the lung. There was no pre-existing bulla or inflammatory lesion associated with this lesion, and the cause of the perforation could not be determined. Histologically, small inflammatory foci associated with abundant lung nematodes were observed in both lung lobes.

Case 9 had right unilateral tension pneumothorax (Fig. 7). Histology revealed few granulomatous lesions around nematodes. No specific cause of the pneumothorax could be detected. Histology of the liver

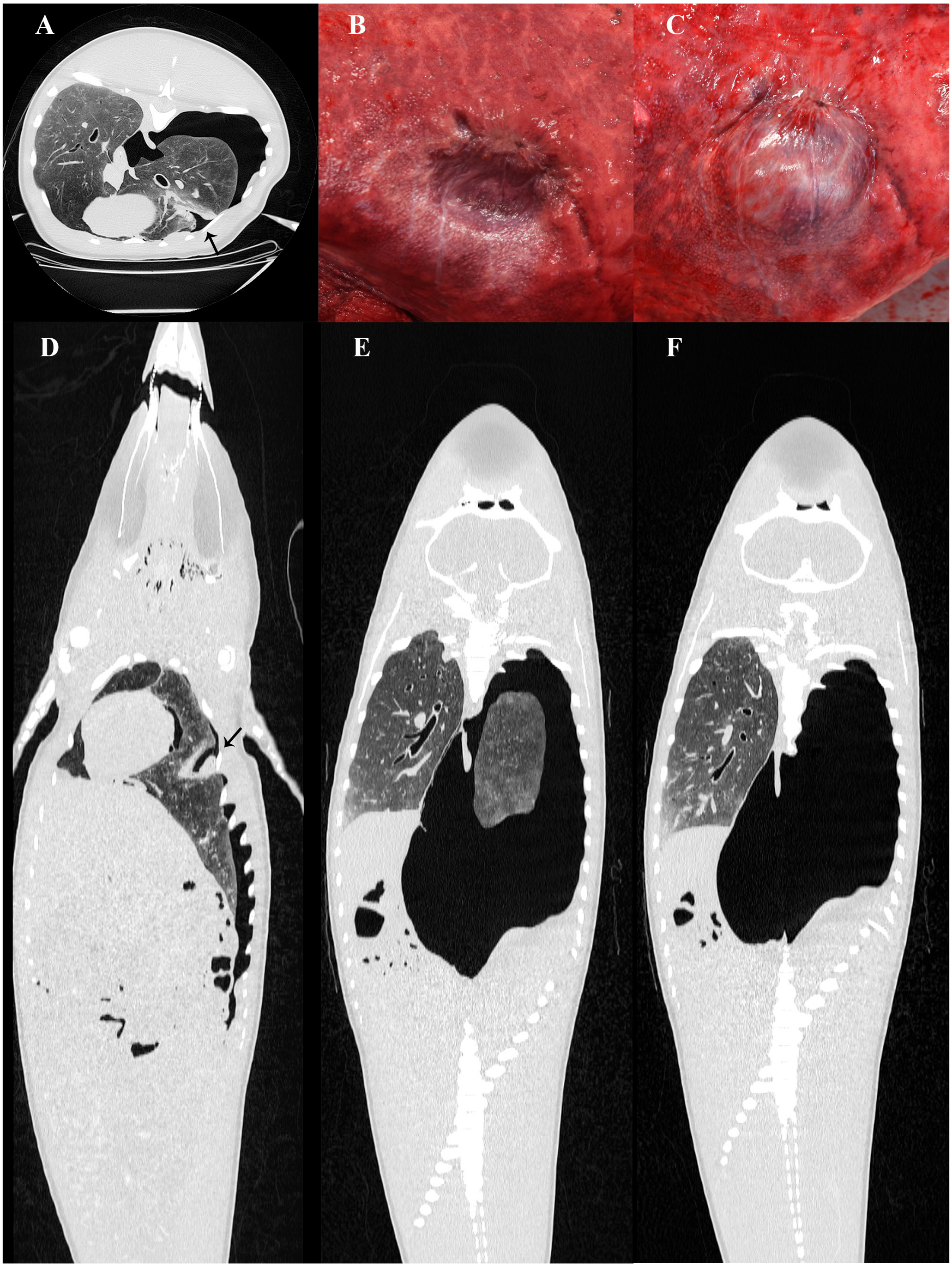

Fig. 4. Case 5. Striped dolphin *Stenella coeruleoalba*. Left-side tension pneumothorax. (A) Transverse CT image in lung window showing a focal indentation (arrow) surrounded by a focal ill-defined soft tissue attenuating alveolar infiltrate. Left-side pneumothorax and displacement of the heart to the right side also visible. (B) Collapsed lung bulla in the lateral aspect of the left lung. (C) Prominent lung bulla after inflation with a tracheal tube. No air leakage was detected by immersion of the lung in water. (D) Dorsal CT reconstruction in lung window at a ventral plane of the thorax showing the pulmonary indentation (arrow) and severe left pneumothorax with lung compression, and mediastinal deviation towards the right side. (E) Dorsal CT reconstruction in lung window at a medium plane of the thorax. Severe distension of the pleural cavity, with midline deviation towards the right side and caudal displacement of the diaphragm. (F) Dorsal CT reconstruction in lung window at a dorsal plane of the thorax. Left lung is so compressed ventrally that is not seen at this level

Fig. 5. Case 6. (A) Common dolphin *Delphinus delphis* with a hook perforating the esophagus and the pleura of the right lung. Left lung has been removed. (B) Hook perforating the esophagus wall and the adjacent pleura of the right lung. (C) View of the esophagus opened, showing the hook attached to the line. Scale is in cm

showed an acute hepatitis associated with the protozoan *Sarcocystis* sp., which was probably, together with pneumothorax, the cause of stranding and death.

4. DISCUSSION

Tension pneumothorax is a severe condition in humans and domestic animals (Leigh-Smith & Harris 2005, Gilday et al. 2021). In humans tension pneumothorax may be associated with mechanical ventilation (Ioannidis et al. 2015), chronic pulmonary disease (Holloway & Harris 2000, Greene et al. 2016, Flower et al. 2020), penetrating chest trauma (McPherson et al. 2006), or barotrauma (Lin et al. 2008). In dogs and cats, trauma, ruptured bullae or blebs, and underlying inflammatory or neoplastic processes are responsible for tension pneumothorax (Kim et al. 2019, Brand et al. 2020, Gilday et al. 2021). In humans, tension pneumothorax is a rare form of spontaneous pneumothorax (Huan et al. 2021). This is in contrast with our experience in dolphins. We describe 9 cases of tension pneumothorax in delphinids. According to findings, 7 of the pneumothorax cases were spontaneous. Primary cases may correspond to individuals with resolved pleural in-

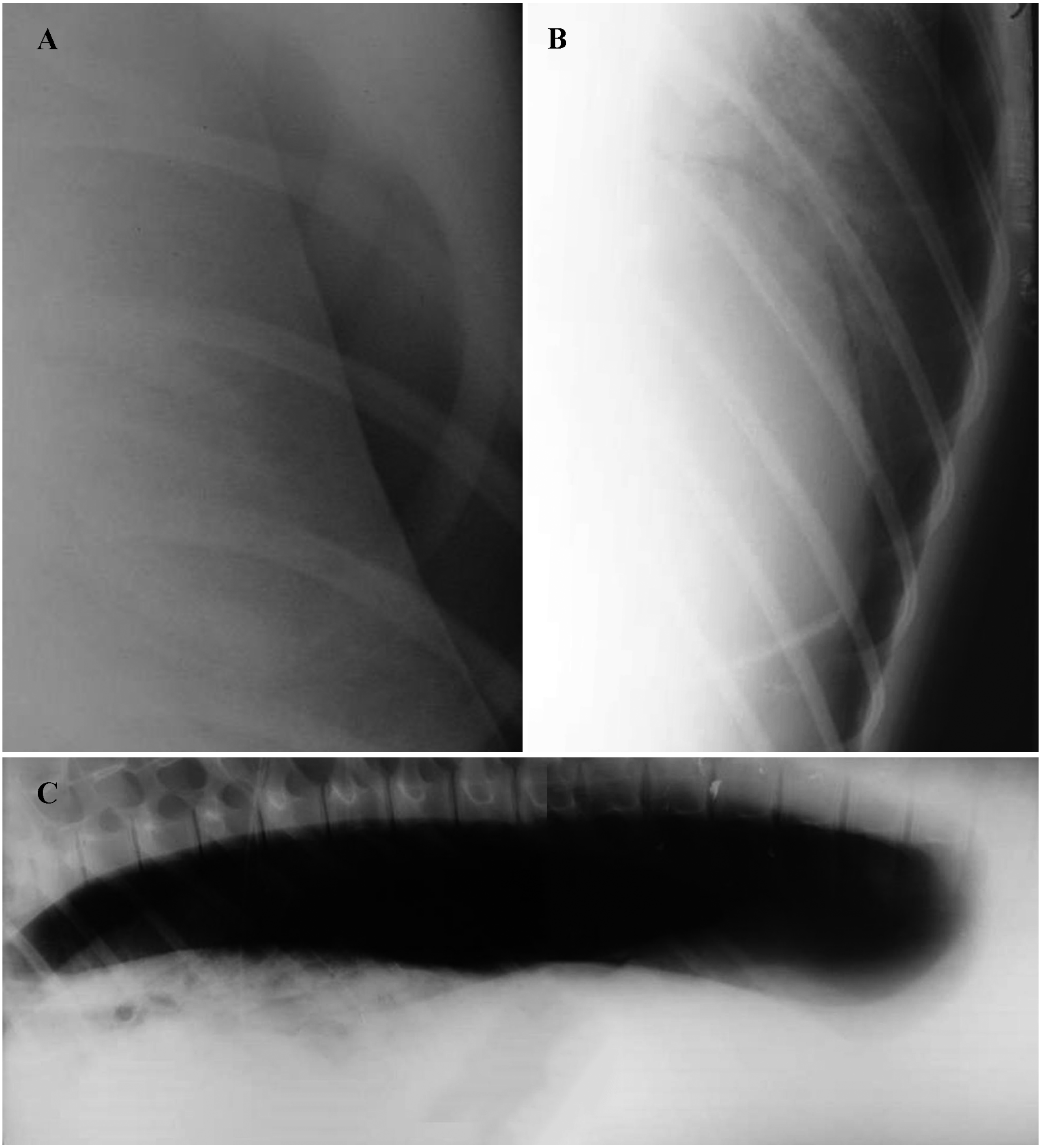

Fig. 6. Case 7. Common bottlenose dolphin *Tursiops truncatus* radiographs showing pneumothorax. (A) Dorso–ventral projection of right hemithorax. Partial right lung collapse and clear accumulation of free air in the pleural space. (B) Recurrent pneumothorax. Moderate accumulation of air in the pleural space observed during one of the pneumothorax relapses. (C) Thorax latero–lateral projection (2 adjoined radiographs). Caudal displacement of the abdomen due to the accumulation of air in the pleural space

juries by the time of death. In the other 2 dolphins, the pneumothorax was traumatic, due to oesophageal perforation or rib fractures. We hypothesize that pneumothorax in dolphins is always (or nearly always) tensional because of their specific anatomical and physiological adaptations to marine life and exposure to pressure changes as diving mammals. Marine mammals are apnoeic divers, and some spe-

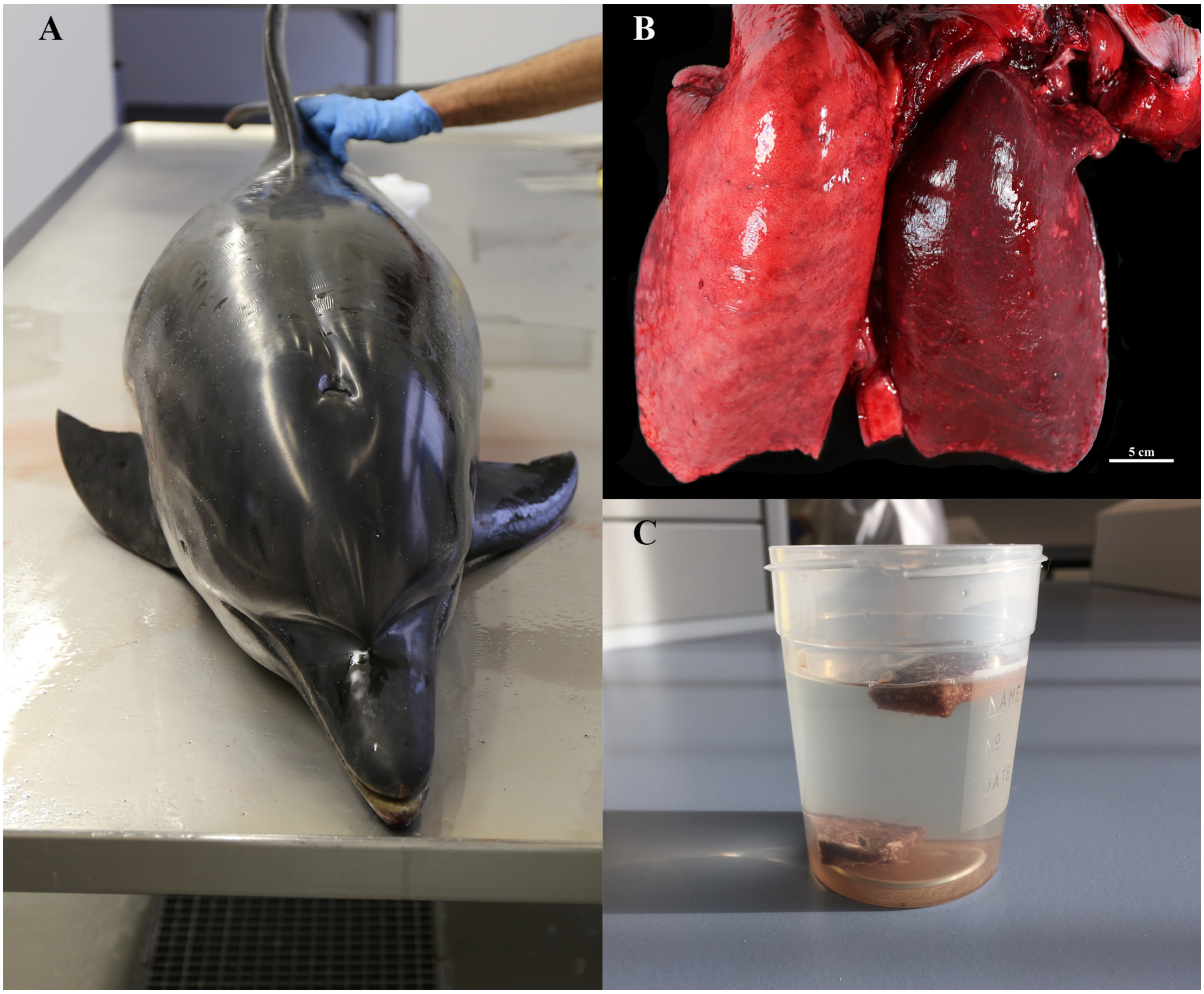

Fig. 7. Case 9. Striped dolphin *Stenella coeruleoalba* with right-side tension pneumothorax. (A) Distension of the right side of the dolphin. (B) Severe atelectasis and reddening of the right lung. (C) Slices of lung tissue in 10% formalin; the right lung sinks, whereas the left lung floats

cies reach remarkable depths and experience notable changes of pressure while diving and returning to the sea surface (Moore et al. 2009). Anatomic adaptations to diving in cetaceans include a highly compliant thorax that allows chest compression, reinforcement of airways with cartilage, septation of airways by smooth muscle sphincters, a thick elastic pleura, and a high collateral interalveolar ventilation (Moore et al. 2011, Piscitelli et al. 2013, Fahlman et al. 2017, Garcia Párraga et al. 2018, Otero-Sabio et al. 2021).

Reports of pneumothorax in marine mammals are scarce, and frequently not further classified as simple or tensional, despite the clinicopathologic relevance of this fact (Leigh-Smith & Harris 2005, Huan et al. 2021). In some cases, however, the tension pneumothorax can be deduced from the morphological description of cases. This is the case of the 8 striped dolphins with pneumothorax of traumatic origin due to inter-specific interaction with common bottlenose dolphins described by Crespo-Picazo et al. 2021, as well as 4 additional cases that appeared after the publication of this article. External lesions included multiple rake marks of variable distribution and severity. Internal macroscopic examination revealed a compendium of traumatic lesions in different organs, with generalized congestion, hematomas, severe hemorrhages and lacerated tissues. Fractured ribs or blunt-force trauma generated perforation of visceral pleura in one or both lungs, and there was severe presence of gas and blood in one or both hemithoraces. Pneumothorax has been then retrospectively subclassified as tension pneumothorax, so these cases strongly support the conclusions of this publication. Biometric data of these cases is included in Table S1 in the Supplement.

Pneumothorax associated with trauma has also been observed in pinnipeds, other cetaceans and manatees (Lightsey et al. 2006, Akmajian et al. 2012, Gerlach et al. 2013). A harbour seal developed a pneumothorax secondary to the perforation of the right lung by a spotted ratfish spine (Akmajian et al. 2012), but the authors did not specify if it was a simple or a tension pneumothorax. A common bottlenose dolphin died several days or weeks after a lung perforation by a stingray spine. Before necropsy, insufflation of the lungs was attempted for optimized visualization of lung parenchyma by CT scan, but the unexpectedly high resistance to air entrance raised the suspicion of a pneumothorax. Air distension of the affected right hemithorax with mild midline deviation (a tension pneumothorax) was confirmed by CT and at necropsy. Insufflation of the lungs may improve visualization at CT scan, as proposed by some authors (Weisbrod et al. 2020, Kuijpers et al. 2022), but also may potentially introduce artefacts in preexisting lung lesions.

In Florida manatees, watercraft-induced trauma is an important cause of death. A review of 713 of these cases detected pneumothorax associated with rib fractures or other unspecified pleural lesions in 11 (1.5%) manatees (Lightsey et al. 2006). The necropsy findings in these cases strongly suggest that the observed pneumothorax was tensional, considering the distended hemidiaphragm by positive pressure, and the abnormal higher buoyancy of the affected hemithorax (Lightsey et al. 2006). In another report, pneumothorax and concurrent pneumoperitoneum were detected in 2 manatee calves (Gerlach et al. 2013). The cause of pneumothorax and pneumoperitoneum was not elucidated in the first calf, which had small amounts of gas in cavities. The second calf had suffered a watercraft-related trauma and had abnormal buoyancy. A CT scan revealed multiple rib fractures with bilateral pneumothorax. Both lungs were collapsed, more severely the right lung, suggesting the potential presence of a tension pneumothorax in this individual. Despite the severity of the lung compression, both manatees survived following a conservative treatment. The peculiar anatomy of the diaphragm in this species, longitudinally anchored to the ventral side of the vertebral bodies and dividing the thorax in 2 separate cavities (Rommel & Reynolds 2000), precludes a midline deviation, which is a frequent feature of tension pneumothorax in other mammals (Leigh-Smith & Harris 2005, Thrall 2013, Kim et al. 2019). In sea otters, pneumothorax has been described in 3 out of 12 individuals with *Coccidioides* sp. pneumonia and granulomatous pleuritis. However, no CT scan or further characterization of the pneumothorax was performed (Huckabone et al. 2015).

Performing a CT scan before postmortem examination, and previous to other manipulations such as cardiac puncture for blood collection, is useful for acquiring pathologic information in marine mammals. In a recent study with 46 harbor porpoises *Phocoena phocoena* examined by CT before necropsy, 5 had lung margin retraction and volume loss of lung lobes and were classified as pneumothorax cases (Kuijpers et al. 2022). Nonetheless, the possibility was not excluded that the presence of gas was the result of autolysis (Kuijpers et al. 2022). However, pneumothorax was not detected at necropsy in any of these cases, even following a modified necropsy procedure with opening of the abdominal cavity first and checking the diaphragm tightness before opening the thoracic cavity. Therefore, the cause and the clinical relevance of the pneumothorax remained unclear for these cases.

We hypothesize that 2 key elements act for tension pneumothorax formation in delphinids, namely (1) a pleural lesion with solution of continuity, and (2) forced leakage of air to the pleural cavity. Whatever the cause of the pleural lesion, it should act as an unidirectional valve, as reported in humans (Leigh-Smith & Harris 2005). What initially occurs as a simple pneumothorax would evolve to a tension pneumothorax due to the normal ventilation mechanics of dolphins, which involves extremely high respiratory flow and high pressure of the incoming and outgoing air (Fahlman et al. 2015). The condition is possibly aggravated by repeated chest collapse on successive dives. While diving, the pressure on the chest leads to alveolar collapse, and air in alveolar spaces is relocated to the airways and sinuses (Moore et al. 2011). However, if a pleural discontinuity exists (with pneumothorax), additional air may reach the pleural cavity until internal and external pressures equalise. After several dives, intrapleural pressure at the sea surface will be so increased that the affected lung will become compressed and atelectatic, the dolphin will show increased buoyancy, and the pressure exerted on the contralateral hemithorax will cause midline deviation and compression of the vena cava, with the corresponding cardiocirculatory compromise. Pain due to chest distention, respiratory insufficiency and increased buoyancy may then limit diving capacity and foraging. The common bottlenose dolphin, which overcame a tension pneumothorax (Case 7), recovered after limitation of diving depth, a fact that supports the role of pressure changes to create a tension pneumothorax.

In summary, this study describes 9 cases of traumatic tension pneumothorax that highlight the relevance of both traumatic injuries and pre-existing lung lesions as causes of tension pneumothorax in delphinids, as observed in humans (Lin et al. 2008, van Berkel et al. 2010) and small domestic animals (Maritato et al. 2009). Factors leading to bulla formation are well known in humans and include pulmonary barotrauma, chronic obstructive pulmonary disease (COPD), cystic fibrosis, pneumonia, connective tissue disorders, neoplasia, and alpha-1-antitrypsin deficiency (Lin et al. 2008, van Berkel et al. 2010). Whether similar factors or other ones, such as obstruction of airways or pleural perforation by lungworms, play a role in bullae formation in dolphins is unknown and requires further study. Lungworms are frequently found in dolphins at necropsy, and in one of our cases (Case 3), the pulmonary bulla had lungworms *Skrjabinalius guevarai* inside. Other Cases (8 and 9) did not present pulmonary bullae, but showed lungworm infection as the only detectable lung lesion.

In live marine mammals, an increased buoyancy is a common clinical sign of tension pneumothorax. Veterinary examination may reveal non-audible vesicular murmurs of the affected hemithorax, as well as ipsilateral lung collapse, caudal displacement of the diaphragm, and lateral displacement of the mediastinum, as in Case 7 (Lightsey et al. 2006, Gerlach et al. 2013). It is possible that the tensional character of a pneumothorax is missed in the necropsies due to the necropsy approach and lack of CT study. Thoracic radiographs are useful to detect a tension pneumothorax antemortem, as well as in cadavers, but CT scan provides superior resolution to detect the presence of gas and pulmonary lesions before necropsy or cardiac puncture are performed. Our findings indicate that, independent of its cause, pneumothorax in cetaceans has a strong potential to become tensional due to anatomical and physiological particularities and the diving activity.

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