Aquatic Mammals 2012, *38*(3), 229-240, DOI 10.1578/AM.38.3.2012.229

Unusual Mortality of Pinnipeds in the United Kingdom Associated with Helical (Corkscrew) Injuries of Anthropogenic Origin

Steve Bexton,[1] Dave Thompson,[2] Andrew Brownlow,[3]
Jason Barley,[4] Ryan Milne,[2] and Cornelia Bidewell[5]

[1]Royal Society for the Prevention of Cruelty to Animals (RSPCA) East Winch Wildlife Centre, King's Lynn, Norfolk, UK
E-mail: eastwinch@rspca.org.uk
[2]Sea Mammal Research Unit (SMRU), University of St Andrews, Fife, UK
[3]Scottish Agricultural College (SAC) Wildlife Unit, Inverness, UK
[4]Agri-Food and Biosciences Institute–Veterinary Sciences Division (AFBI-VSD) Stormont, Belfast, UK
[5]Animal Health and Veterinary Laboratories Agency (AHVLA), Rougham Hill, Bury St Edmunds, UK

Abstract

Between June 2008 and December 2010, 76 dead pinnipeds were found on the coast of the United Kingdom with peculiar injuries consisting of a single continuous curvilinear skin laceration spiralling down the body. The skin and blubber had been sheared from the underlying fascia and, in many cases, the scapula also had been avulsed from the thoracic wall. Although previously unreported in the UK, similar distinctive lesions had been described in Canadian pinnipeds where they were referred to as *corkscrew injuries*. In the UK, identical injuries were seen in both native species of pinniped, with 43 harbor seals (*Phoca vitulina*) (57%) and 26 grey seals (*Halichoerus grypus*) (34%) affected, and seven carcasses (9%) for which the species could not be determined. There were two apparent seasonal peaks in incidence; predominantly adult harbor seals were discovered during the summer and juvenile grey seals during the winter. *Postmortem* examinations of 20 harbor seals revealed they had been alive and healthy when the injuries were sustained, with no evidence of any underlying disease or disability. Based on the pathological findings, it was concluded that mortality was caused by a sudden traumatic event involving a strong rotational shearing force. The injuries were consistent with the animals being drawn through the ducted propellers of marine vessels and, in some cases, there was a direct correlation with the presence of work boats operating in the vicinity. This challenges the conclusions of a previous study in Canada that suggested natural predation by Greenland sharks (*Somniosus microcephalus*) was likely to be responsible for these injuries.

Key Words: corkscrew, seal, pinniped, anthropogenic mortality, mechanical, spiral, stranding, propeller

Introduction

Stranded marine mammals are an important resource for investigating natural disease, environmental contaminants, and human-related interactions in the wild (Gerber et al., 1993; Dierauf, 1994). Traumatic injuries can be caused by natural events such as predation, intraspecies aggression, scavenger activity, and interactions with natural features (Gulland et al., 2001), or they may result from human activity such as encounters with maritime vessels, fisheries (Stroud & Roffe, 1979; Gerber et al., 1993; Goldstein et al., 1999), and man-made marine debris (Shaughnessy, 1980; Fowler, 1987; Stewart & Yochem, 1987; Croxall et al., 1990; Goldstein et al., 1999).

Traumatic injuries in marine mammals can be difficult to investigate because events usually happen at sea with no witnesses. Despite this, differentiation between natural and anthropogenic causes is often possible based on the gross evidence available (Read & Murray, 2000); and in many cases, the causative agent can be established due to the diagnostic appearance of the lesions (Read & Murray, 2000; Lightsey et al., 2006).

In recent years, dead pinnipeds have been found with peculiar helical wounds. These bear little resemblance to any previously recognised injuries, suggesting a novel mechanism is responsible (Anonymous, 1998; Lucas & Natanson, 2010). These highly distinctive lesions consist of a continuous smooth skin laceration that starts at the head and spirals down the body, making between one and three revolutions around the trunk, terminating at a point between the ribcage and the pelvis. The wound edge is characteristically smooth with no serrations; the skin and blubber is sheared from the body, exposing large areas of tissue; and in many cases, the fore flippers are avulsed from the axial skeleton at the scapular joint. The distinctive helical wound shape has led to them being referred to as *corkscrew injuries*.

The earliest documented report of this type of injury dates from 1993 when 95 dead seals (predominantly grey seals) stranded on Sable Island, Nova Scotia (Lucas & Natanson, 2010). Hundreds of seal carcasses with identical injuries continue to be washed ashore on the island every year, and researchers there have suggested predation by Greenland sharks (*Somniosus microcephalus*) may be involved (Lucas & Natanson, 2010).

In 1998, the bodies of over a 1,000 immature harp seals (*Pagophilus groenlandica*) washed ashore on Prince Edward Island in the Gulf of St Lawrence. Many were found to have circumferential and spiral lacerations similar to those reported on Sable Island, although the actual cause of the mass mortality was undetermined (Anonymous, 1998).

Since June 2008, dead pinnipeds with remarkably similar helical lesions have also been discovered in the United Kingdom. This paper describes the prevalence, species, ages, and distribution of these cases, and the pathological findings from 20 necropsies. The diagnostic criteria of the corkscrew injury are also described to assist in the identification of future cases.

Materials and Methods

Reports of stranded pinnipeds with corkscrew injuries were obtained from wardens of the National Trust, Norfolk Police, Sea Mammal Research Unit, Scottish Marine Animal Stranding Scheme, Agri-Food and Biosciences Institute (Northern Ireland), and individual members of the public visiting coastal areas. Most reported sightings were accompanied by detailed witness descriptions and confirmed by photographic evidence. Some reports were received retrospectively following increased publicity surrounding the phenomenon. Information including the date, strand location, species, and age-class was recorded. Additionally, between June 2008 and November 2010, 20 carcasses with characteristic lesions were retrieved from the shore and transported to the nearest wildlife pathology investigation centre for *postmortem* examination (Royal Society for the Prevention of Cruelty to Animals [RSPCA] East Winch Wildlife Centre, King's Lynn; Scottish Agricultural College [SAC] Veterinary Investigation Centre, Inverness; Sea Mammal Research Unit [SMRU], St Andrews; Agri-Food and Biosciences Institute–Veterinary Sciences Division [AFBI-VSD], Belfast; and Animal Health Veterinary Laboratories Agency [AHVLA], Bury St Edmunds). Standard necropsies were performed according to established techniques for marine mammals (Geraci & Lounsbury, 1993; Dierauf, 1994; Rowles et al., 2001). Whole body radiographs were obtained for eight carcasses to demonstrate any skeletal injuries that might be present and to highlight any radio-dense foreign material such as hooks, gunshot, other metallic material, or fragments of shark tooth. In some individuals, the damaged skin edges were re-approximated and temporarily sutured in place to accurately visualise the wound pattern. Body diagram drawings were produced to document the location, size, and shape of the wounds (see Figure 1), and individual lesions were photographed. The skin was closely inspected for trace evidence such as paint, oil, metal, tooth fragments, and any other foreign material. Where appropriate, tissues were fixed in 10% formalin and prepared for standard histological examination by embedding in paraffin, sectioning at 6 to 8 μm, and staining with haematoxylin and eosin.

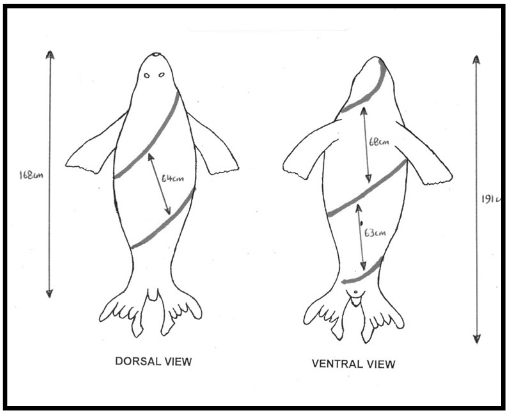

Figure 1. Body diagram showing typical helical wound shape

The lesions were compared with known causes of injury in pinnipeds to investigate possible aetiologies. The species and age-class of confirmed cases were analysed for any trends, and the area where each stranded seal was retrieved was explored for possible natural or anthropogenic contributing factors.

Results

A total of 76 pinnipeds with characteristic corkscrew injuries was recorded in the UK between June 2008 and December 2010 (Table 1). The species most frequently affected was the harbor seal (*Phoca vitulina*), comprising 43 (57%) of the reported cases, with 26 grey seals (*Halichoerus grypus*) next at 34%, along with seven carcasses (9%) for which the species was not identified (Table 1). Of the harbor seals for which sex was recorded, 25 were

Table 1. Summary of pinnipeds with corkscrew lesions reported in the United Kingdom, 2008-2010

Date	No.	Species	Sex	Age	Location	Grid ref.	Necropsy	Photo
05/06/2008	1	H	F	A	West Sands, St Andrews, SCOTLAND	HO498192	N	N
16/06/2008	1	H	F	A	West Sands, St Andrews, SCOTLAND	HO498192	Y (SAC)	Y
23/03/2009	2	U	U	U	Blakeney Point, Norfolk, ENGLAND	TG037457	N	Y
04/07/2009	1	H	F	A	Tentsmuir Fife, SCOTLAND	NO509263	N	Y
06/07/2009	1	H	F	A	Tentsmuir Fife, SCOTLAND	NO505269	N	Y
30/07/2009	1	H	F	J	Eden Estuary, St Andrews, SCOTLAND	NO485191	Y (SAC)	Y
30/07/2009	1	H	M	J	Eden Estuary, St Andrews, SCOTLAND	NO486191	Y (SAC)	Y
06/12/2009	1	G	M	J	Inchkeith Firth of Forth, SCOTLAND	NT293826	N	Y
Winter 09/10	8	G	U	U	Blakeney Point, Norfolk, ENGLAND	Various	N	Y
March 10	3	G	U	U	Blakeney Point, Norfolk, ENGLAND	TF995463	N	N
April-June 2010	6	H	U	U	Blakeney Point, Norfolk, ENGLAND	Various	N	N
May-June 2010	2	U	U	U	Salthouse/Cley, Norfolk, ENGLAND	U	N	N
07/06/2010	1	H	F	A	Eden Estuary, St Andrews, SCOTLAND	NO494206	N	Y
10/06/2010	1	G	M	A	Fife Ness, SCOTLAND	NO637100	N	Y
10/06/2010	1	H	U	U	Blakeney Point, Norfolk, ENGLAND	TG001458	N	Y
15/06/2010	1	H	F	A	Eden Estuary, St Andrews, SCOTLAND	NO495209	N	Y
16/06/2010	1	H	F	A	Eden Estuary, St Andrews, SCOTLAND	NO494204	Y (SAC)	Y
22/06/2010	1	H	F	A	Eden Estuary, St Andrews, SCOTLAND	NO496211	N	Y
25/06/2010	1	H	F	A	Monifieth Tayside, SCOTLAND	NO502321	N	Y
30/06/2010	1	H	U	U	Blakeney Point, Norfolk, ENGLAND	TG001458	N	Y
12/07/2010	1	H	F	A	Blakeney Point, Norfolk, ENGLAND	TF992464	Y (RSPCA)	Y
13/07/2010	1	H	U	U	Blakeney Point, Norfolk, ENGLAND	TF9946	N	Y
14/07/2010	1	H	U	U	Blakeney Point, Norfolk, ENGLAND	TF988445	N	Y
15/07/2010	1	H	U	U	Blakeney Point, Norfolk, ENGLAND	TF9946	N	Y
16/07/2010	1	H	F	A	Blakeney Point, Norfolk, ENGLAND	TF991464	Y (AHVLA)	Y
19/07/2010	1	H	F	Imm	Blakeney Point, Norfolk, ENGLAND	TG0146	Y (RSPCA)	Y
19/07/2010	1	H	F	Imm	Blakeney Point, Norfolk, ENGLAND	TF991464	Y (RSPCA)	Y
20/07/2010	1	H	F	A	Blakeney Point, Norfolk, ENGLAND	TG006466	Y (RSPCA)	Y
21/07/2010	1	H	F	A	Blakeney Point, Norfolk, ENGLAND	TF9946	Y (RSPCA)	Y
21/07/2010	1	U	U	U	Blakeney Point, Norfolk, ENGLAND	TF988445	N	Y
22/07/2010	1	U	U	U	Blakeney Point, Norfolk, ENGLAND	TG0146	N	Y
23/07/2010	1	H	F	A	Blakeney Point, Norfolk, ENGLAND	TF992464	Y (RSPCA)	Y
25/07/2010	1	H	F	A	Blakeney Point, Norfolk, ENGLAND	TG006466	Y (RSPCA)	Y
26/07/2010	1	U	U	U	Blakeney Point, Norfolk, ENGLAND	TF995465	N	Y

Abbreviations: H = harbor seal, G = grey seal, A = adult, J = juvenile, Imm = immature, F = female, M = male, U = unknown

Table 1. continued

Date	No.	Species	Sex	Age	Location	Grid ref.	Necropsy	Photo
27/07/2010	1	H	F	A	Blakeney Point, Norfolk, ENGLAND	TF992465	Y (RSPCA)	Y
27/07/2010	1	H	F	A	Blakeney Point, Norfolk, ENGLAND	TG002455	Y (RSPCA)	Y
28/07/2010	1	H	F	A	Blakeney Point, Norfolk, ENGLAND	TF989458	Y (RSPCA)	Y
28/07/2010	1	H	F	A	Eden Estuary, St Andrews, SCOTLAND	NO492210	N	Y
03/08/2010	1	H	U	U	Blakeney Point, Norfolk, ENGLAND	TF996466	N	N
03/08/2010	1	H	F	A	Blakeney Point, Norfolk, ENGLAND	TF990459	Y (RSPCA)	Y
24/08/2010	1	H	U	A	Ardrosan, SCOTLAND	NS223429	N	Y
24/08/2010	1	G	F	Imm	Ardrossan, SCOTLAND	NS224429	N	Y
26/08/2010	1	H	F	A	Eden Estuary, St Andrews, SCOTLAND	NO462195	N	Y
27/10/2010	1	H	U	A	Aberdeen, SCOTLAND	NJ969054	N	Y
01/11/2010	1	H	F	Imm	Kircubbin, Strangford Lough, NORTHERN IRELAND	NW7115	Y (AFBI)	Y
01/11/2010	1	H	M	Imm	Kircubbin, Strangford Lough, NORTHERN IRELAND	NW7115	Y (AFBI)	Y
01/11/2010	1	H	U	Imm	Kircubbin, Strangford Lough, NORTHERN IRELAND	NW7115	Y (AFBI)	Y
10/11/2010	1	H	M	A	Grey Abbey, Strangford Lough, NORTHERN IRELAND	NW6921	Y (AFBI)	Y
25/11/2010	1	G	F	A	Fife Ness, SCOTLAND	NO638099	N	Y
03/12/2010	2	G	U	J	Kirkhaven Isle of May, SCOTLAND	NT659991	N	Y
10/12/2010	5	G	U	J	Kirkhaven Isle of May, SCOTLAND	NT659991	N	N
14/12/2010	2	G	U	J	Isle of May, SCOTLAND	Various	N	N
14/12/2010	1	G	M	J	Copinsay Orkney, SCOTLAND	HY609013	N	Y
15/12/2010	1	G	U	A	Fife Ness, SCOTLAND	NO631103	N	Y

Abbreviations: H = harbor seal, G = grey seal, A = adult, J = juvenile, Imm = immature, F = female, M = male, U = unknown female (89%), and of these, 21 were adults (84%) (Figure 2a). Thirty-two harbor seals (86%) were found in the summer months of June, July, and August (Figure 2b). Of the grey seals for which age-class was determined, 11 were juveniles (73%) (Figure 2a); there was also a seasonal peak for this species with 12 of the total number (67%) found in December (Figure 2b). Pinnipeds with characteristic lesions were recorded in England, Scotland, and Northern Ireland, with apparent hotspots in Norfolk, England (42) and Fife, Scotland (16), which together accounted for 76% of the recorded UK cases.

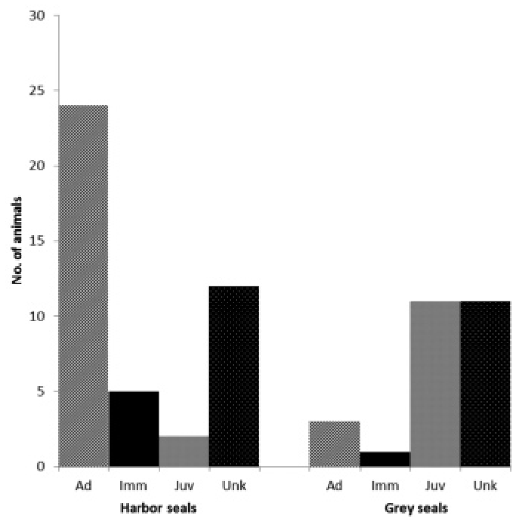

Figure 2a. Age structure of pinnipeds with corkscrew injuries in United Kingdom (2008-2010)

Postmortem examinations were performed on 20 harbor seals with corkscrew lesions between June 2008 and November 2010. There were 12 adult females; three subadult females; and one each of adult male, immature male, juvenile male, juvenile female, and an immature animal of undetermined sex. The main pathological findings are summarised in Table 2, and the typical gross appearance is shown in Figure 3. In all cases, the corkscrew lesion was considered to be the cause of death due to the extent and severity of the injury. There was no evidence of any underlying disease or disability, although additional investigative procedures such as histology and microbiology were prevented by decomposition in most carcasses. Most of the animals had been in good nutritive condition (18), and 10 had remains of recently eaten food in the stomach. Obvious bruising, considered indicative of *antemortem* injury, was present in nine cases, although similar changes in further carcasses could have been obscured by decomposition. In addition to the main corkscrew injury, all the animals had lesions to the head, including lacerations to the muzzle and/or trauma to the skull consistent with a traumatic frontal impact. Patterned injuries consisting of a series of regularly spaced linear or triangular lesions were also present in five individuals (Figure 4).

Discussion

Pinniped carcasses with distinctive corkscrew wounds have been identified at different locations throughout the UK since 2008, and in Canada since 1993. Seventy-six carcasses were recorded in the UK between June 2008 and December 2010; however, the true number of cases is likely to be higher due to under-reporting, misdiagnosis,

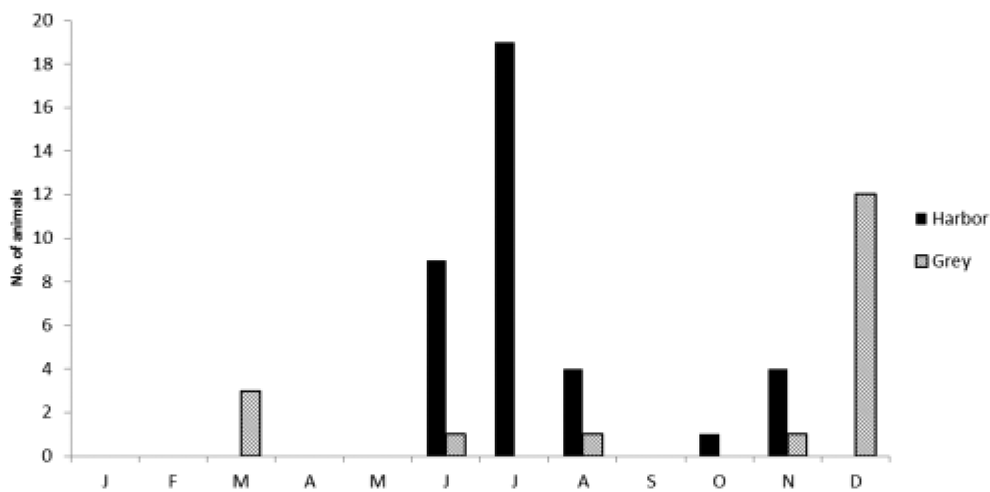

Figure 2b. Month of stranding of pinnipeds with corkscrew injuries in UK (2008-2010)

Table 2. Summary of main pathological findings

Necropsy finding	Number (N = 20)
1. Continuous helical skin laceration originating at the head and spiralling down the body terminating between the ribcage and pelvic area (*corkscrew wound*) (Figure 3)	20 (100%)
2. Skin and blubber sheared from the underlying fascia with connective tissue attachments torn caudolaterally (Figure 3)	20 (100%)
3. Scapular attachments to the axial skeleton severed and the fore flipper partially degloved	18 (90%)
4. Wound edge smooth and perpendicular or angled slightly caudally to the axis of the body, with hairs immediately adjacent to the wound uncut	20 (100%)
5. Bruising, notably to the neck, thoracic inlet, and/or sternum consistent with blunt trauma to the chest area	9 (45%)
6. Animals in good physical condition with adequate blubber reserves	18 (90%)
7. Food remains in the stomach consistent with recent feeding activity prior to death	10 (50%)
8. Radiographic confirmation of the absence of foreign material such as metal fragments, hooks, gunshot, or embedded tooth fragments	8 (100% of those radiographed)
9. Absence of any additional significant gross pathological changes indicative of underlying disease or injury	20 (100%)
10. Absence of any significant histopathological changes	4 (100% of histological examinations)
11. No significant tissue loss associated with wounds	20 (100%)
12. Lesions to the head, including slice wounds on the muzzle or skull fractures with lesion orientation consistent with a frontal impact	19 (95%)
13. Patterned injuries comprising a series of linear or triangular wounds or abrasions 15 mm in length and 12 to 15 mm apart (see Figure 4)	5 (25%)

Figure 3. Typical gross appearance of corkscrew injuries

Figure 4. Regularly spaced triangular claw-like lesions lateral to right nostril

carcasses not reaching land, carcasses stranding in remote and inaccessible locations, and the lack of a coordinated national reporting system for dead pinniped strandings in the UK.

A corkscrew injury is defined pathologically as a continuous curvilinear laceration that spirals down the body, combined with severe avulsion (degloving) of the skin and blubber from the underlying fascia. Despite occurring in many different geographical areas, both in the UK and Canada, the corkscrew lesions are remarkably consistent in all cases, suggesting a common mechanism is responsible. Degloving injuries are generally caused by a tangential (shearing) force applied across the skin (Kudsk et al., 1981). In humans, they are sometimes called wringer and roller injuries because they were traditionally associated with the rotating moving parts of clothes wringers or industrial rollers (MacCollum, 1938; Kudsk et al., 1981; Antoniou et al., 2005). Nowadays, most human avulsion injuries are sustained during vehicle collisions, especially when the skin is entrapped against a spinning wheel (Kudsk et al., 1981; Antoniou et al., 2005). Similar avulsion injuries are occasionally seen in cats that rest in the engine compartment of a parked vehicle. When the vehicle is started, the sudden high speed rotation of the fan belt can result in the skin being torn from the underlying tissue (Aiello, 1998). Avulsion of the skin and blubber in pinnipeds requires considerable mechanical force and the corkscrew injuries are consistent with a powerful rotational shearing force similar to the above scenarios.

The injuries bore little resemblance to previously recognised causes of trauma in pinnipeds: a boat propeller strike typically produces a series of deep, parallel, regularly spaced lacerations, usually to the flank or dorsum (Goldstein et al., 1999; Gulland et al., 2001; Wood, 2001; Lightsey et al., 2006); entanglement in discarded rope, netting, and other man-made debris usually results in the material becoming wrapped around the neck causing deep circumferential wounds (Stroud & Roffe, 1979; Bonner & McCann, 1982; Fowler, 1987; Stewart & Yochem, 1987; Goldstein et al., 1999); and shark attack generally results in a characteristic U-shaped bite mark with a serrated edge and tooth marks, although, to the authors' knowledge, shark predation has never been confirmed in the UK (Brodie & Beck, 1983; Alcorn & Kam, 1986; Lucas & Stobo, 2000; Gulland et al., 2001) (see Figures 5a, 5b & 5c). Pinnipeds can also be injured during intraspecific fighting, by dog attacks, and by falling on rocks and other natural features, resulting in puncture wounds and abrasions, mostly to the flippers and ventrum (Stroud & Roffe, 1979).

Postmortem examinations revealed the majority of seals were in a good nutritive state with adequate blubber reserves and no signs of any underlying disease or disability. Contusions, indicating the trauma had occurred *antemortem* (Riviello, 2010), were present in nine individuals, and may have been obscured in others due to *postmortem* change. The injuries were very severe and extensive and would have caused significant haemorrhage, resulting in shock and rapid death. The majority of carcasses that wash ashore have probably died relatively close to where they are found (Wilson et al., 2007), especially when they are freshly dead and therefore have not been in the water for very long. All locations where corkscrew seals have been found have been relatively shallow coastal waters with sand or gravel seabed, but no other common factors link them such as unusual fishing methods, sand and gravel extraction, military or naval operations, wave or tidal energy systems, underwater turbines, or large pelagic predators.

Figure 5a. Parallel chop wounds from propeller strike

Figure 5b. Neck collar lesion due to entanglement in marine debris

Figure 5c. Bite profile associated with attack by a shark (Courtesy of John Mosier, Pelagic Shark Research Foundation)

Previous researchers in Canada proposed that Greenland sharks could be responsible for the lesions (Lucas & Natanson, 2010). They suggested the sharks grasp the seal with their jaws and then spin around their axis causing the seal's skin to split, claiming the helical wound shape is due to a natural tendency of pinniped skin to cleave in this fashion (Lucas & Natanson, 2010).

Greenland sharks are a deep, cold water species that naturally inhabit circumpolar regions between -0.6 and 10° C (although they have also occasionally been observed foraging in relatively shallow estuaries in temperatures up to 12° C) (Harvey-Clark et al., 2005; Stokesbury et al., 2005). Although not uncommon in Canada, they are rare in British waters (Vas, 1991; Peirce, 2008). Moreover, they are extremely unlikely to be found in the coastal waters around Blakeney in July (where many of the seal bodies were discovered) because the mean sea temperature at that time is 17.5° C (Norris, 2001), well above the upper limit of the temperature range for this cold-adapted species (Chris Harvey-Clark, 12 August 2010, pers. comm.). They may have the potential to be opportunistic predators, although this has yet to be documented in the literature (Harvey-Clark et al., 2005), and they are regarded as primarily a scavenger species (Fisk et al., 2002; Skomal & Benz, 2004; Stokesbury et al., 2005; Yano et al., 2007). Their diet consists mainly of fish, but a variety of different animal remains, including pinnipeds, have been found in their stomach contents (Fisk et al., 2002; Skomal & Benz, 2004; Yano et al., 2007).

There are several other inconsistencies with the Greenland shark theory. The pinnipeds in the current study all had facial and/or skull injuries consistent with a frontal impact, with caudally directed tissue avulsion, suggesting they had all been injured head-first. Predators rarely attack from the front, and sharks typically ambush their prey from behind or beneath, inflicting a fatal wound, and then wait for their prey to die (Stroud & Roffe, 1979; Gulland et al., 2001). Crucially, none of the seals at necropsy had any actual bites; and when the skin edges were realigned into anatomic apposition, there was no missing tissue or other evidence of shark feeding such as tooth marks, serrations, or tooth fragments embedded in tissue. It is unlikely that sharks would expend the energy to attack and kill an animal, and then discard the body. Additionally, an adult pinniped is capable of inflicting a nasty bite in self-defence, and a shark would not risk such injury unless intending to consume the prey. Furthermore, predators usually target weaker individuals (Stroud & Roffe, 1979), but most animals in the present study were healthy and in good physical condition and are therefore more typical of a sudden traumatic event.

Pinniped integument is relatively resistant to lacerations and abrasion, especially on the ventral body surfaces, which are often in direct contact with rough abrasive terrain when hauled out (Rommel & Lowenstine, 2001). The epidermis is quite thick, and the connective tissue in the dermis contains many elastic fibres (Rommel & Lowenstine, 2001). The adipose tissue of the hypodermis is also reinforced by collagen and elastic fibres making it comparatively rigid (Reynolds & Rommel, 1999). In the authors' experience, pinniped integument is relatively difficult to incise and tear and shows no natural propensity to cleave circumferentially. Although there are anatomical cleavage lines that follow the collagen fibres in the dermis, called Langer's lines, there is no evidence that pinniped skin naturally splits in the precise helical pattern characteristic of the corkscrew injuries as suggested by Lucas & Natanson (2010).

Certain pathological lesions are considered to be diagnostic indicators of anthropogenic trauma (Read & Murray, 2000). The corkscrew laceration was clean, sharp, and uninterrupted, suggesting it had been produced in a single smooth stroke. This was consistent with the continuous regular motion of machinery, and the wound edges displayed no imperfections or variations that are typical of natural causes.

No significant mechanical devices were identified in the local areas other than maritime vessels, and these were generally comprised of regular fishing boats, small commercial vessels, and some recreational boats. Most of these vessels have conventional screw propellers that would not cause corkscrew lesions if a seal was struck, but would instead result in pathognomic parallel chop wounds (Figure 5a) (Goldstein et al., 1999; Gulland et al., 2001; Wood, 2001; Lightsey et al., 2006). However, workboats, including tugs, multipurpose work vessels, and offshore support vessels were also occasionally operating in all of the locations, and, in some areas, particularly in Norfolk, there appeared to be a correlation between such vessels and the seal injuries. These vessels are often equipped with propellers housed within cylindrical nozzles or other thrust-augmenting devices (e.g., kort nozzles or azimuth thrusters) to improve efficiency and manoeuvrability, especially at high thrust and low speeds (Gaston, 2002; Carlton, 2007). These devices possess the components needed to create the corkscrew injuries—namely, rotating blades and powerful mechanical shearing forces—and also generate a strong suction effect that is known to pull objects through (Carlton, 2007). A marine mammal encountering a ducted propeller would not sustain chop wounds because the tip of the blade is shielded by the nozzle and the clearance between the outer edge of the blade and the inner surface of the nozzle is very small (Carlton, 2007). However, if the propeller duct was of sufficient diameter to accommodate the body of a seal, the seal could be drawn through the device while suspended in the stream of fast moving water. Because of its hydrodynamic body contour, the seal could pass between the rotating blades, encountering the leading blade edge, thus resulting in a helical laceration down the body (Figure 6b). The strong shearing force would cause avulsion of the skin and blubber, but significant lateral crushing injuries would be avoided because the force was primarily directed

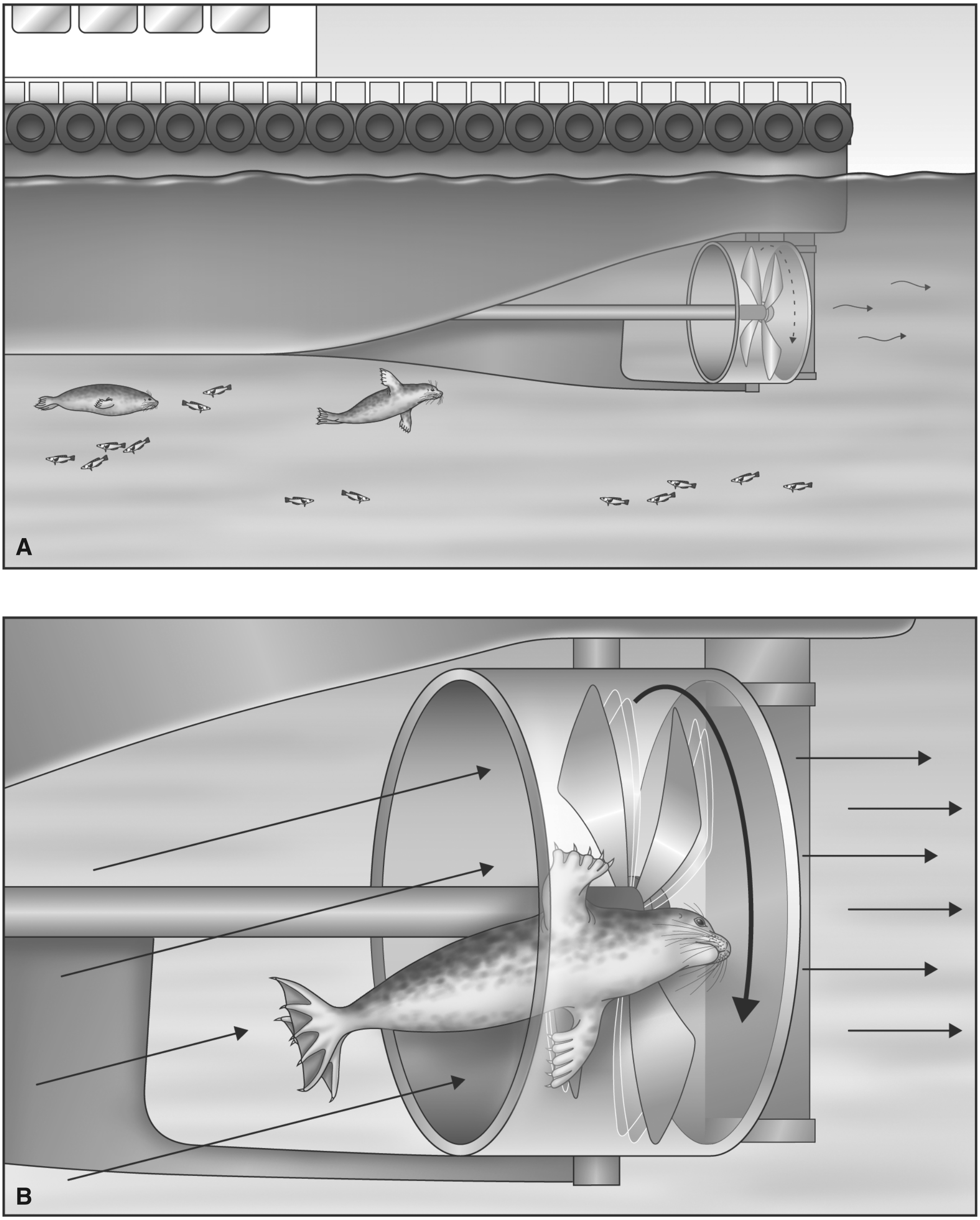

Figure 6. Seal injuries in propellers (Author: Steve Bexton BVMS MRCVS; Artist: Debbie Maizels [debbie@zoobotanica.com])

tangentially. The only appendages projecting from the pinniped body are the fore flippers, and, in many cases, these had been torn from the body at the scapular joint consistent with this mechanism. The skull injuries seen in some seals may be the result of the initial impact with the rotating blade as the animal enters head first. Further evidence may be provided by the patterned injuries present on some bodies which consisted of regularly spaced identical lacerations (Figure 4) or imprint abrasions that could correspond to an initial encounter with a structure forward of the nozzle such as a rudder or rope cutter.

Healthy marine mammals have good sensory function and agility in water, meaning they are generally capable of avoiding or evading such hazards (Wilson et al., 2007). The trauma was sustained head-first, suggesting the seals initially approached the device rather than being randomly struck, raising the possibility that they had been attracted to it for some reason. In order to pass through the propeller, the seal must be beneath the hull of the vessel facing the stern (Figure 6a). This would be more likely if the vessel had a flat-bottomed hull and was stationary or moving very slowly. Floating bodies, such as stationary vessels, can act as fish aggregation devices, and the presence of fish could potentially attract seals to feed below the hull. The modern electric motors used on many of these vessels are comparatively quiet, and the propellers capable of sudden rapid operation with little warning when dynamic positioning systems are active. It is also possible the seals are being attracted to certain propellers because their acoustics mimic seal vocalisations. The disruptive effects of turbidity and noise pollution are also possible factors involved (Wilson et al., 2007), and reduced visibility caused by sediment disturbance (e.g., propeller wash) or noise distraction caused by machinery or offshore construction work also need further investigation.

In both the UK and Canada, there appears to be a seasonal pattern to the seal mortality, with predominantly harbor seals (mostly adult females) affected in the summer months and juvenile grey seals during the winter (Lucas & Natanson, 2010). This may reflect seasonal differences in feeding behaviour with female harbor seals staying close to shore during the summer breeding season (Thompson, 1993). In winter, recently independent juvenile grey seals also initially remain inshore close to the breeding colony, exposing them to increased risk if vessels are operating in these shallow coastal waters at the same time.

The pathological findings in the 20 harbor seals examined in this study are consistent with the animals having been pulled through ducted propellers. In some cases, there was an apparent correlation between the appearance of carcasses on shore and the presence of work boats operating in the vicinity, although a direct causal link was difficult to establish because of a lack of witnesses and the indeterminable time between seal death and stranding. The first reports of corkscrew injuries came from Sable Island in the early 1990s, which coincided with the installation of offshore oil and gas projects on the Scotian shelf close to the island. The first recorded cases in the UK appear to coincide with the recent expansion of the offshore renewable energy industry and the associated increase in work boat activity in littoral waters. Further research, including laboratory scale experiments, is necessary to confirm the exact causal mechanism involved. It is also important to identify the precise vessel characteristics and operational conditions that result in these seal deaths, including why the seals are apparently being drawn to these devices, in order to understand the problem and develop long-term mitigation measures. Assuming many carcasses do not make it ashore, the potential impact of this phenomenon could be much greater and could even be having negative effects at a population level.

Acknowledgments

The field work necessary for this study was supported by several organisations, particularly the National Trust and Norfolk Police. Special thanks particularly to Mike Brown, Jason Pegden, David Wood, and Ed Stubbings for retrieving carcasses for *postmortem* examination. We also thank the staff and volunteers at the RSPCA, SAC, SMRU, AFBI, and AHVLA Diseases of Wildlife Scheme for their assistance and facilities; Ken Pye for back track analysis; and Abbey Veterinary Services and Sandra Scholes for histological examinations. We are also grateful to Chris Harvey-Clark, Sean Van Sommeran, and James Wood for their helpful comments and suggestions throughout the investigations.

Literature Cited

Aiello, S. E. (Ed.). (1998). *The Merck veterinary manual* (8th ed.). Whitehouse Station, NJ: Merck & Co., Inc.

Alcorn, D. J., & Kam, A. K. H. (1986). Fatal shark attack on a Hawaiian monk seal (*Monachus schauinslandi*). *Marine Mammal Science, 2*, 313-315.

Anonymous. (1998). Mass mortality of young harp seals. *Canadian Cooperative Wildlife Health Centre: Newsletters & Publications*, *5*(2), 6-7. Lincoln: University of Nebraska.

Antoniou, D. A., Kyriakidis, A., Zaharopoulos, A., & Moskoklaidis, S. (2005). Degloving injury: Report of two cases and review of the literature. *European Journal of Trauma*, *31*(6), 593-596. http://dx.doi.org/10.1007/s00068-005-1059-3

Bonner, W. N., & McCann, T. S. (1982). Neck collars on fur seals, *Arctocephalus gazella*, at South Georgia. *British Antarctic Survey Bulletin, 57*, 73-77.

Brodie, P., & Beck, B. (1983). Predation by sharks on the grey seal (*Halichoerus grypus*) in eastern Canada. *Canadian Journal of Fisheries and Aquatic Sciences*, *40*, 267-271. http://dx.doi.org/10.1139/f83-040

Carlton, J. (2007). Propulsion systems. In *Marine propellers and propulsion* (2nd ed., pp. 11-30). Oxford, UK: Butterworth-Heinemann (Elsevier).

Croxall, J. P., Rodwell, S., & Boyd, I. L. (1990). Entanglement in man-made debris of Antarctic fur seals at Bird Island, South Georgia. *Marine Mammal Science*, *6*(3), 221-233. http://dx.doi.org/10.1111/j.1748-7692.1990.tb00246.x

Dierauf, L. A. (1994). *Pinniped forensic, necropsy and tissue collection guide* (NOAA Technical Memorandum NMFS-OPR-94-3). Washington, DC: National Oceanic and Atmospheric Administration.

Fisk, A. T., Tittlemier, S. A., Pranschke, J. L., & Norstrom, R. J. (2002). Using anthropogenic contaminants and stable isotopes to assess the feeding ecology of Greenland sharks. *Ecology*, *83*(8), 2162-2172. http://dx.doi.org/10.1890/0012-9658(2002)083[2162:UACASI]2.0.CO;2

Fowler, C. W. (1987). Marine debris and northern fur seals: A case study. *Marine Pollution Bulletin*, *18*(6), 326-335. http://dx.doi.org/10.1016/s0025-326x(87)80020-6

Gaston, M. J. (2002). *The tug book.* Yeovil, Somerset, UK: Patrick Stephens Limited.

Geraci, J. R., & Lounsbury, V. J. (1993). Specimen and data collection. In J. R. Geraci & V. J. Lounsbury (Eds.), *Marine mammals ashore: A field guide to strandings* (Chapter 10). Galveston: Texas A&M University Sea Grant College Program.

Gerber, J. A., Roletto, J., Morgan, L. E., Smith, D. M., & Gage, L. J. (1993). Findings in pinnipeds stranded along the central and northern California coast 1984-1990. *Journal of Wildlife Disease*, *29*(3), 423-433.

Goldstein, T., Johnson, S. P., Phillips, A. V., Hanni, K. D., Fauquier, D. A., & Gulland, F. M. D. (1999). Human-related injuries observed in live stranded pinnipeds along the central California coast 1986-1998. *Aquatic Mammals*, *25*(1), 43-51.

Gulland, F. M. D., Lowenstine, L. J., & Spraker, T. R. (2001). Noninfectious diseases. In L. A. Dierauf & F. M. D. Gulland (Eds.), *CRC handbook of marine mammal medicine* (2nd ed., pp. 521-547). Boca Raton, FL: CRC Press. http://dx.doi.org/10.1201/9781420041637.ch23

Harvey-Clark, C. J., Gallant, J. J., & Batt, J. H. (2005). Vision and its relationship to novel behaviour in St Lawrence River Greenland sharks, *Somniosus microcephalus. Canadian Field Naturalist*, *119*(3), 355-359.

Kudsk, K. A., Sheldon, G. F., & Walton, R. L. (1981). Degloving injuries of the extremities and torso. *Journal of Trauma*, *21*(10), 835-839.

Lightsey, J. D., Rommel, S. A., Costidis, A. M., & Pitchford, T. D. (2006). Methods used during gross necropsy to determine watercraft-related mortality in the Florida manatee (*Trichechus manatus latirostris*). *Journal of Zoo and Wildlife Medicine*, *37*(3), 262-275. http://dx.doi.org/10.1638/04-095.1

Lucas, Z. N., & Natanson, L. J. (2010). Two shark species involved in predation on seals at Sable Island, Nova Scotia, Canada. *Proceedings of the Nova Scotian Institute of Science*, *45*(2), 64-88.

Lucas, Z., & Stobo, W. T. (2000). Shark-inflicted mortality on a population of harbour seals (*Phoca vitulina*) at Sable Island. *Journal of Zoology*, *252*(3), 405-414. http://dx.doi.org/10.1111/j.1469-7998.2000.tb00636.x

MacCollum, D. W. (1938). Wringer arm: A report of twenty-six cases. *New England Journal of Medicine*, *218*, 549-554.

Norris, S. W. (2001). *Near surface sea temperatures in coastal waters of the North Sea, English Channel and Irish Sea – Volume 2* (CEFAS Science Series Data Report Number 40). Lowestoft, UK: Centre for Environment, Fisheries and Aquaculture Science.

Peirce, R. (2008). *Sharks in British Seas*. Bude, Cornwall, UK: Shark Cornwall.

Read, A. J., & Murray, K. T. (2000). *Gross evidence of human-induced mortality in small cetaceans* (NOAA Technical Memorandum NMFS-OPR-15). Washington, DC: National Oceanic and Atmospheric Administration.

Reynolds, J. E., & Rommel, S. A. (Eds.). (1999). *Biology of marine mammals.* Washington, DC: Smithsonian Institution Press.

Riviello, R. J. (Ed.). (2010). *Manual of forensic emergency medicine: A guide for clinicians.* Sudbury, MA: Jones & Bartlett Publishers.

Rommel, S. A., & Lowenstine, L. J. (2001). Gross and microscopic anatomy. In L. A. Dierauf & F. M. D. Gulland (Eds.), *CRC handbook of marine mammal medicine* (2nd ed., pp. 129-163). Boca Raton, FL: CRC Press. http://dx.doi.org/10.1201/9781420041637.sec2

Rowles, T. K., van Dolah, F. M., & Hohn, A. A. (2001). Gross necropsy and specimen collection protocols. In L. A. Dierauf & F. M. D. Gulland (Eds.), *CRC handbook of marine mammal medicine* (2nd ed., pp. 449-470). Boca Raton, FL: CRC Press. http://dx.doi.org/10.1201/9781420041637.ch21

Shaughnessy, P. D. (1980). Entanglement of Cape fur seals with man-made objects. *Marine Pollution Bulletin*, *11*, 332-336. http://dx.doi.org/10.1016/0025-326X(80)90052-1

Skomal, G. B., & Benz, G. W. (2004). Ultrasonic tracking of Greenland sharks (*Somniosus microcephalus*), under Arctic ice. *Marine Biology*, *145*, 489-498. http://dx.doi.org/10.1007/s00227-004-1332-8

Stewart, B. S., & Yochem, P. K. (1987). Entanglement of pinnipeds in synthetic debris and fishing net and line fragment at San Nicolas and San Miguel Islands, California 1978-1986. *Marine Pollution Bulletin*, *18*(6), 336-339. http://dx.doi.org/10.1016/s0025-326x(87)80021-8

Stokesbury, M. J. W., Harvey-Clark, C., Gallant, J., Block, B. A., & Myers, R. A. (2005). Movement and environmental preferences of Greenland sharks (*Somniosus microcephalus*) electronically tagged in the St Lawrence Estuary, Canada. *Marine Biology*, *148*, 159-165. http://dx.doi.org/10.1007/s00227-005-0061-y

Stroud, R. K., & Roffe, T. J. (1979). Causes of death in marine mammals stranded along the Oregon coast. *Journal of Wildlife Disease*, *15*, 91-97.

Thompson, P. M. (1993). Harbour seal movement patterns. In I. L. Boyd (Ed.), *Marine mammals: Advances in behavioural and population biology* (Symposium of the Zoological Society of London, Vol. 66, pp. 225-239). London: Academic Press.

Vas, P. (1991). A field guide to the sharks of British coastal waters. *Field Studies*, *7*, 651-686.

Wilson, B., Batty, R. S., Daunt, F., & Carter, C. (2007). *Collision risks between marine renewable energy devices and mammals, fish and diving birds: Report to the Scottish Executive.* Oban, Scotland, UK: Scottish Association for Marine Science.

Wood, J. L. (2001). *A simple and effective method for analysing propeller marks on manatees in Brevard County, Florida, USA*. Retrieved 5 July 2012 from www.lumatrex.com/SimplePropellerMarkAnalysis.htm.

Yano, K., Stevens, J. D., & Compagno, L. J. V. (2007). Distribution, reproduction and feeding of the Greenland shark (*Somniosus microcephalus*), with notes on two other sleeper sharks *Somniosus pacificus* and *Somniosus antarcticus*. *Journal of Fish Biology*, *70*(2), 374-390. http://dx.doi.org/10.1111/j.1095-8649.2007.01308.x