GROSS AND HISTOLOGIC EVIDENCE OF SHARP AND BLUNT TRAUMA IN NORTH ATLANTIC RIGHT WHALES (EUBALAENA GLACIALIS) KILLED BY VESSELS


Abstract: Vessel-whale collision events represented the ultimate cause of death for 21 (52.5%) of the 40 North Atlantic right whales (Eubalaena glacialis) necropsied between 1970 and December 2006. Injuries seen in vessel-struck whales fall into two distinct categories: 1) sharp trauma, often resulting from contact with the propeller, and 2) blunt trauma, presumably resulting from contact with a vessel’s hull. This study analyzes four trauma cases that resulted from vessel-whale collisions, which together provide a framework for a more critical understanding of lethal blunt and sharp trauma resulting from vessel collisions with right whales. In case no. 1, contact with a propeller resulted in three deep lacerations. The animal survived acute trauma only to succumb nearly 14 years later when the lesions reopened and became infected. In case no. 2, anecdotal reports linked the laceration of large arteries of the peduncle and histologic evidence of perimortem trauma at a bone fracture site to vessel-whale collision trauma. Case no. 3 had a laceration of the oral rete and a fracture of the rostrum. Both of the areas displayed histologic evidence of perimortem blunt trauma. Finally, in case no. 4, an antemortem mandibular fracture, two additional skull fractures, and widespread hemorrhage were consistent with severe blunt trauma. Evidence from each case, including the timing of trauma relative to the time of death and identifying characteristics of both trauma types, are presented. Before this study, no detailed comparative analysis of trauma pathology that resulted from lethal interactions between vessels and right whales had been conducted. This study demonstrates the importance of detailed gross and histologic examination in determining the significance and timing of traumatic events. This work represents a new paradigm for the differential diagnosis of lethal sharp and blunt trauma in right whales hit by ships and will enhance the present understanding of the impact of anthropogenic mortality on this critically endangered species.

Key words: Eubalaena glacialis, fracture, propeller, right whale, ship-strike, trauma.

INTRODUCTION

The North Atlantic right whale (Eubalaena glacialis) population, currently composed of fewer than 400 known individuals, is inhibited from recovery by low reproductive success and high anthropogenic mortality that may contribute to the extinction of the species within 200 years.5,10,18–20 The two primary sources of anthropogenic mortality identified in this population include entanglement in fishing gear and vessel-whale collisions.15,18–20,26 Between 1970 and December 2006, 21 right whales were involved in fatal vessel-whale collisions as determined by necropsies.26,30 Because this represents the cause of death of more than half (52.5%) of the 40 individuals necropsied during that time period, the reduction of vessel-whale collision mortality has been identified by the United States and Canadian governmental agencies as an important goal of their respective right whale management programs.7,20,27,28

Physical trauma seen in right whales struck by vessels falls into two distinct, although not mutually exclusive, categories: sharp trauma and blunt trauma. Sharp trauma is caused when sharp underwater protuberances, including propellers and rudders, come into contact with the animal. Propeller trauma occurs when the rotating blades of the vessel’s screw incise the soft tissue, and sometimes the bone, of the animal. This type of trauma provides the most obvious external evidence of injury. Blunt trauma results when the animal is struck by the hull of the vessel. These events typically leave little external evidence of the injury, even in the most severe cases, because of the thickness of soft tissue and the dark pigment of much of the epidermis, which tends to obscure evidence of swelling and bruising.26
Although the earliest confirmed case of lethal sharp trauma in right whales is from 1976, propeller injury in large whales of known and unspecified species (which, therefore, may have included right whales) can be found in the literature dating as far back as 1877.\cite{Wood} Sharp trauma results in peracute tissue damage, with variable levels of severity, ranging from mild nonfatal "knicks" to severe immediately lethal wounds, or more chronic sequelae (see Case study I). Damage from a turning propeller leaves a characteristic series of more or less parallel, evenly spaced, curved (s-shaped or z-shaped) cuts that deepen at the center and become shallow toward the margin, as seen in Figure 1 (Wood, pers. com.).\cite{Moore} Propeller laceration margins may extend to variable levels of the epidermis, hypodermis, blubber, or skeletal muscle.

Analysis of epidermal scarring suggests that 7%
of the population has healed wounds that are consistent with sublethal sharp trauma.\textsuperscript{14,19} In minor cases, sharp trauma can lead to blood loss, infection via open wounds, scarring, and behavioral response to contact, including avoidance of a stimulus.\textsuperscript{18,22,26} In severe cases, sharp trauma can lead to deep disruption of underlying soft tissue, extensive blood loss, and dismemberment. Lethal cases may involve severe damage to the vertebral column or the axial muscle, resulting in reduced locomotor function, or, in extreme cases, the complete separation of the animal into two parts.

Blunt trauma that results from a vessel-whale collision is marked by hemorrhage, edema, and, often, a concomitant premortem fracture or displacement of skeletal elements. Hemorrhage and edema may be observed in the affected blubber, subdermal sheath, and skeletal muscle. Generally, the epidermis is not disrupted, and there is little external evidence to indicate the presence or the extent of subdermal injury, although swelling and bruising are at times evident externally. For this reason, complete forensic necropsy, including systematic flensing and examination of soft tissue and skeletal elements, is the only true diagnostic tool available for the differential diagnosis of trauma from a vessel-whale collision as the primary cause of death when a collision was not documented.\textsuperscript{25,26} Internal viscera are often autolyzed in these rapidly decomposing carcasses, although evidence of traumatic perforations of the gastrointestinal tract or active foraging may provide insight into the perimortem disposition of the whale.\textsuperscript{13}

Previously, the standard classification of injury from vessel collisions with right whales included four somewhat overlapping and often coincident categories, namely, 1) acute propeller trauma, 2) severed fluke, 3) bone fracture, and 4) hemorrhage and hematoma.\textsuperscript{19} At this time, there is no detailed analysis of the nature or timing of trauma pathology that resulted from lethal interactions with sharp and blunt vessel structures. This study analyses four trauma cases and provides a framework for a more critical definition of lethal blunt trauma and sharp trauma in right whales. The characterization of injuries seen in right whales struck by vessels will aid processors in assessing future necropsy findings of tissue trauma and linking them to their underlying causes and timing of trauma relative to the time of death. Future determinations based on this trauma classification scheme will provide more accurate vessel-whale collision mortality statistics and will help inform managers of the impact of vessel-whale collision mitigation efforts.

**MATERIALS AND METHODS**

The examination of the four animals discussed here was conducted according to the currently accepted right whale necropsy protocol to the extent practical.\textsuperscript{23} Lesions, including affected and unaffected margins, were sampled for histology. The condition of the carcass was evaluated according to standard condition codes for marine mammals.\textsuperscript{13} The condition of the remains is not directly proportional to the time since death but, instead, categorizes the appearance of the carcass. Code two is fresh. Code three is moderately decomposed. Code four is significantly decomposed. Code five is mummified. Necropsy reports for these animals include the known history of the animal, based on prior reports and field observation, carcass discovery and retrieval, and gross necropsy. Each report culminates with the findings of postnecropsy laboratory analyses and diagnosis. These reports can be obtained via a request for data access to the Right Whale Consortium.\textsuperscript{30}

**RESULTS**

The forensic necropsy observations and test results of four individual North Atlantic right whales that suffered trauma from vessel strikes and that were examined between October 2003 and January 2005 are presented below, beginning with the most recent case. Available life history data for each case are summarized in Table 1.

**Case study I—Eg no. 2143**

Eg no. 2143 was first sighted in 1991 as a calf with its mother in the right whale calving grounds off the southeastern U.S. coast. At that time, it had three deep, open wounds on its left flank that had the characteristic parallel pattern and curvature of propeller wounds. Despite the severity of these wounds and a poor prognosis for survival, Eg no. 2143 was resighted in the Bay of Fundy 6 months later and was observed each consecutive year through 2003. It was last seen alive on 5 January 2005 off the Florida coast. At the time of its death, the animal was pregnant with its first known fetus. The code three carcass of Eg no. 2143 was found 30 km east of Cumberland Island, Georgia, on 12 January 2005.

Three large, healed propeller wounds were visible on the left abdominal wall and were perpendicular to the long axis of the animal (Fig. 2). The cranial-most lesion consisted of inactive scar tissue and was limited to the dorsum. When in the supine position, the lesion was not visible. The central wound was also composed of inactive uncompro-
### Table 1. Life history and necropsy findings from four right whales killed by vessels.

<table>
<thead>
<tr>
<th>Eg no.</th>
<th>Necropsy location and date</th>
<th>Sex</th>
<th>Age, y, min. age*</th>
<th>Pregnant?</th>
<th>Condition code</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>2143</td>
<td>Cumberland Island, Georgia Jan 2005</td>
<td>F</td>
<td>13</td>
<td>Yes</td>
<td>3</td>
<td>Sharp trauma. Succumbed to sequelae of propeller trauma nearly 14 years after injury.</td>
</tr>
</tbody>
</table>

*Numbers followed by a “_/H11001/” represent the “minimum age” for individuals first identified as juveniles or adults.

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**Figure 2.** Close up of caudal (left) and central (right) propeller scars on left flank of right whale Eg no. 2143. The whale is oriented with the caudal end to the left of the image, cranial end to the right, lying on its dorsum with its ventral surface facing up. The caudal scar was opened from the epidermis through the subdermal sheath perpendicular to the longitudinal axis of the body. Copious ectoparasitic cyamids were associated with the wounds and are visible here as small beige dots. The caudal (left) and central wounds are visible here, the cranial-most scar is out of the frame. Photographer: Alicia Windham-Reid, Florida Fish and Wildlife Conservation Commission.
mised scar tissue and measured approximately 209-cm curved length. The cranial margin of the lesion’s ventral origin was 585-cm from the center of the eye. The caudal lesion measured approximately 210-cm curved length. The caudal margin of the lesion’s ventral origin was 687-cm from the center of the eye. This lesion had an open region that made the axial muscle visible. Other than the propeller wounds, there were no significant findings of human interaction, blunt trauma, or fractures.

The cervix and caudal margin of the uterus appeared normal, and a full-term female fetus was found in the thoracic cavity and was necropsied separately. It was suspected that the fetus was forced cranially through a rupture in the diaphragm, perhaps as a result of the purging of gases associated with putrefaction. The uterine horns, ovaries, cranial margin of the uterus, gastrointestinal tract (from the esophagus to the intestine), larynx, lungs, and trachea were not found.

The most remarkable finding was the caudal propeller lesion. The caudal scar extended between the dorsal and lateral lines at the level of the genital slit. It included an active, open wound that exuded large amounts of green pus and was 53-cm long and 16-cm wide. The active region of the caudal scar was open from the epidermis through the subdermal sheath, which left deep axial muscle clearly visible. The dorsal margin of the active site was 27-cm from the dorsal tip of the caudal lesion. Although the axial muscle examined in other parts of the body appeared normal, the muscle deep to this wound was liquefied in a cranially oriented cone shape, and, when opened, it explosively released approximately 5 L of tan mucopurulent debris. Torn tendons and muscle fibers were associated with both the cranial and caudal margins of the wound. The lesions and exudate were surrounded by hard connective and scar tissue approximately 0.5-m thick.

Microscopic examination of cranial and caudal scar tissue revealed irregular and undulating superficial epithelium and neutrophilic infiltration of the papillary and superficial reticular dermis (Fig. 3). There was extensive fibrosis, with little associated inflammation in the middle and deep dermis and adipose tissue (Fig. 4).

Findings indicate that severe, sublethal propeller trauma had delayed but ultimately fatal complications. Secondary intention wound healing may have resulted in decreased strength and compromised integrity of tissues injured by the propeller. Potential complications, including sepsis secondary to bacteremia via the open caudal propeller scar, likely arose as a result of girth expansion during pregnancy, which led to loss of scar tissue integrity, wound reopening, and severe infection.

**Case study II—Eg no. 1909**

Eg no. 1909 was first sighted as a calf in 1989. It was seen each consecutive year from 1989 to 2003. It was last seen on 21 April 2003 in the Great South Channel. At the time of its death, the cow was pregnant with its first known fetus. The code three carcass was found on shore 24 November 2004 at Ocean Sands, North Carolina.

The left fluke blade was completely severed, and large dorsal and ventral arteries (2- to 3-cm in diameter) that originated in the tail stock were lacerated and exposed along the midline (Fig. 5). A deep, linear laceration was observed in the soft tissue superficial to the left caudal third of the rostrum. The lesion extended through the epidermis, deep into the premaxilla. A small amount of tissue bridging was evident, and the exposed margins of the wound were brown-green in color, similar to the thick pasty fluid that coated the underlying bone. When viewed in dorsoventral cross section, mild, abruptly demarcated hemorrhage was observed, which extended 1 cm around the margin of the lesion.

Examination of the blubber layer and postcranial skeletal elements revealed no additional evidence of trauma. A linear soft tissue wound (approximately 11.6-cm deep) was seen through the rostrum and the premaxilla. The linear laceration, perpendicular to the longitudinal axis of the body, extended from the left lateral lip to the dorsal midline into the premaxilla. This wound measured approximately 1-cm wide by 15-cm long. This lesion was associated with two lesions in the underlying bone and hemorrhage that extended 5-cm around the wound in the overlying soft tissue. The first bone lesion was a linear laceration into the premaxilla that measured approximately 1.5-cm across and 8.5-cm long. A second lesion was a “v-shaped” laceration into the left premaxilla.

A near-term female fetus, between 3- to 4-m long, was found in the thoracic cavity and was necropsied separately. As was discussed previously, in the case of Eg no. 2143, postmortem decomposition and gas buildup presumably led to increased abdominal pressure and a rupture of the diaphragm, followed by extrusion of organs through the pharynx.

An analysis of soft tissue from the wound overlying the premaxilla revealed marked necrotizing and hemorrhagic panniculitis. Also evident were mild multifocal hemorrhage in adipocyte lobules and mild multifocal to coalescing intermysial ede-
ma, with separation of fine collagen bundles consistent with traumatic “stretching.” A bone sample from the damaged premaxilla had a comminuted fracture. Microscopic examination of decalcified bone revealed bone fractures that involved individual or multiple trabeculae. The fracture margins were irregular, and the margin surface was covered with extravasated erythrocytes and small amounts of an eosinophilic substance consistent with fibrin.

Laceration of the large vessels of the peduncle and tissue trauma to the rostrum and the premaxilla suggest extensive trauma to both the fluke and the head, accompanied by significant blood loss, which led to traumatic, hypovolemic shock. Extravasated erythrocytes, fibrin deposition, and trabecular fracture of the premaxilla support the acute, perimortem nature of these injuries as opposed to postmortem or chronic lesions.

These findings are consistent with two reports of a bleeding whale seen on 17 November 2004 and later received by the Virginia Aquarium and Marine Science Center Stranding Program. A general public report described a whale, with a fresh wound to its tail, that was moving slowly just off the coast of North Carolina. The whale was reportedly bleeding and was missing a large portion of its fluke when seen at 12:00 PM. A second report received from the U.S. Navy 5 days later detailed a vessel-whale collision event that involved a Navy Amphibious Assault Ship on 17 November 2004 at 10:46 AM. Global Positioning System coordinates from the public report placed the whale 4 nautical miles southwest of the naval whale strike coordinates. The close proximity (in both time and space) make it likely that the same whale was seen by both vessels and was in all probability Eg no. 1909 that washed ashore 7 days later.

Case study III—Eg no. 1004

Eg no. 1004 was first seen as an adult in 1975. Eg no. 1004 was last seen alive in the Great South Channel on 29 May 2003 and was pregnant with...
its sixth known offspring at the time of its death. The early code three carcass of Eg no. 1004 was necropsied in February 2004 in Nags Head, North Carolina.

There was no evidence of fresh or recent human interaction on the epidermis, although white, healed scarring from old fishing gear entanglements was found on the ventral peduncle and on the left side at the angle of the mouth and trailed cranially to the mid arch of the lingual surface of the left lip. The posterior insertion of both flippers also exhibited white, healed entanglement scars. There was a slight discoloration and bulging near the caudal insertion of the left mandible that was consistent with subdermal edema. A deep incision through the epidermis, blubber, and muscle was made just caudal to the skull down to the atlanto-occipital joint, with the animal lying on its dorsum. This incision revealed substantial hemorrhage and edema in the subdermal sheath that extended from the nuchal crest through the right lateral midline to the ventral subdermal sheath (Fig. 6).

There were areas of hemorrhage deep to the blubber on both the ventral and dorsal aspects of the animal at the level of the subdermal sheath and muscle. Edema, corresponding to the external swelling, was found in the subdermal sheath and muscle overlying the left mandible (Fig. 7). Dorsal edema extended along the dorsal midline from the blowhole, caudally to the anus, and was 5-cm deep. Dorsal edema extended laterally to the midline on the left side at the level of the posterior insertion of the axilla and crossed the dorsal midline to the right lateral midline. Ventral edema extended from the posterior insertion of the left flipper caudally to the insertion of the peduncle. Ventral edema extended laterally to the midline just caudal to the anus.

Examination of the oral cavity revealed a laceration in the oral rete overlying a fracture of the rostrum (Fig. 8). The area of baleen that surrounded the oral rete laceration was coated in a thick yellow-brown fluid in a spray-like pattern that emanated from the laceration. Upon removal of soft

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**Figure 4.** Dermis from propeller scar. Within the superficial dermis, there is deposition of abundant mature collagen (C) with few entrapped adipocytes (A). 200×. Photographer: David Rotstein, University of Tennessee.
tissue, a complete transverse fracture of the rostrum, maxilla, premaxilla, and vomer was evident at the site of the laceration. Displacement was observed; however, it is unknown how much displacement resulted from carcass handling versus the initial trauma. The fracture plane of each bone was sampled for histology. Postcranial skeletal elements showed no signs of fracture or damage. The fetus was necropsied separately, although no significant findings were recorded.

Hemorrhagic tissue, irregular margins of fracture plane, and adherent fibrillar material localized at the vomer and maxillary fracture sites were suggestive of perimortem fractures of the vomer, premaxilla, maxilla, and rostrum. Microscopic observation of pallor in tissues from the colon, uterus, and cervix were consistent with exsanguination or blood loss because of shock.

A combination of severe subdermal bruising found in dorsal and ventral tissues, complete fracture of the rostrum that involved the maxilla, premaxilla, and vomer; and severe laceration of oral rete that resulted in rapid loss of blood directly contributed to the death of Eg no. 1004. This evidence suggests death resulted from traumas associated with catastrophic impact with a vessel.

**Case study IV—Eg no. 2150**

Eg no. 2150 was first sighted as an animal of unknown age in Massachusetts Bay in 1991. It was last seen alive off the coast of Georgia in February 2002. The code four carcass of Eg no. 2150 was necropsied in Culloden Cove, Nova Scotia, Canada, in October 2003.

Photographs taken during the initial encounter on 2 October 2003 were viewed after the necropsy. The images revealed a large area of epidermal discoloration and swelling overlying the right mandible, although most of the epidermis was absent when the animal was necropsied 2 days later. Despite extreme autolysis, the main findings upon internal examination included deep subdermal hemorrhage in the blubber, subdermal sheath, and muscle overlying the right mandible; abnormal fluids and substances noted in the abdominal and thoracic cavities; and three distinct fractures in the skull.

There was a closed (simple), linear, longitudinal fracture along the caudal aspect of the cranium...
Figure 6. View of right side of postcranial cross section of Eg no. 1004 after decapitation reveals the first signs of extensive blunt trauma. The animal is lying ventral-side up. The black epidermis (right), overlying the creamy white blubber layer, is superficial to a gelatinous layer of hemorrhagic tissue and brown (autolysed) muscle (all tissue to the left of the blue scale bar in hand). The 5-cm-thick hemorrhagic tissue is consistent with perimortem blunt trauma. Photographer: Regina Campbell-Malone, Woods Hole Oceanographic Institution.

(Fig. 9). The fracture plane extended from the mid-sagittal plane at the dorsal margin of the fracture through the occipital bone approximately 20-cm to the left of the foramen magnum. The ventral margin of the fracture extended through the base of the occipital, such that it was completely dissociated with the lateral aspects separated by a 15- to 30-cm gap. The fracture measured approximately 1.5-m in length and communicated with the brain case. Soft tissue overlying this cranial vault fracture was too autolyzed to permit the detection of discoloration, edema, or hemorrhage associated with a perimortem fracture. Severe bruising was noted in the connective tissue and muscle overlying a fractured right lower jaw (Fig. 10a, b), although the blubber layer was unremarkable. All postcranial skeletal elements were intact. Disarticulated right ribs were associated with hemorrhage near the axilla of the right flipper. There were three distinct fractures in the cranial skeleton. The right mandible was completely fractured approximately 1.5-m from the mandibular symphysis. A fracture of the left rear of the vomer was also found (not pictured).

Histologic analyses of bone fragments revealed that the mandibular fracture plane contained regions of necrotic bone (demonstrated by the presence of fibrous tissue and islands of cartilage), collagen (as confirmed by Masson trichrome), and woven bone (not shown). These were considered abnormal and indicative of bone healing and,
Figure 7. Schematic representation of subdermal hemorrhage and edema in right whale Eg no. 1004. Both the dorsal and ventral surfaces were extensively bruised. Except for bruising overlying the left mandible, bruising seen on right side (not shown) mirrored that seen on the left side. Image from Eg no. 1004 necropsy report adapted from standard right whale necropsy protocol.25,30

Figure 8. Evidence of significant blood loss in oral cavity of right whale Eg no. 1004. Inspection of the roof of the mouth revealed a laceration to the oral rete (between two arrows) and apparent "blood-spatter" staining (traced by gray curve) on the lingual surface of baleen plates. The tongue and black lip can be seen at the bottom of the photograph. Removal of soft tissue revealed a complete fracture of the rostrum, vomer, and premaxilla. Staining pattern indicates that vessel contents were under pressure when the laceration occurred, thereby providing evidence of peri-mortem trauma. Photographer: Regina Campbell-Malone, Woods Hole Oceanographic Institution.
potentially, an antemortem disease process. Histologic analysis of the bone fragments from the fractured vomer and cranium revealed no evidence of inflammatory or repair response. Gross evidence of hemorrhage in the soft tissue overlying these fractures would allow them to be conservatively classified as perimortem trauma.

The ultimate cause of death was traumatic injury that resulted from skull fractures subsequent to a vessel-whale collision. The applied stress was sufficient to result in a longitudinal fracture along the caudal aspect of the skull, which compromised the brain case, with complete dissociation along the ventral aspect of the occipital bone. Histologic evidence indicates that this lethal strike may have been preceded either by an earlier, nonfatal strike that fractured the right mandible or a perimortem mandibular fracture of a section of the jawbone weakened by preexisting disease.

DISCUSSION

These four cases present evidence of traumatic and ultimately lethal encounters between vessels and whales. The types of tissue damage identified...
Figure 10. Internal signs of hemorrhage and a complete fracture of the right mandible of right whale Eg no. 2150. 

**a.** Hemorrhage discovered upon reflection of skin and blubber layer. A knife penetrates the plane of the complete transverse fracture of the right mandible (seen in **b**). 


during necropsy can be evaluated and categorized by using the diagnostic characteristics of sharp and blunt trauma, thus creating an effective field standard to which future forensic necropsy cases can be compared. Findings that are important to the discussion include the overall health and nutritional status of the individual, the relative timing of skeletal fractures compared with the time of death of
the animal, and the categorization of sharp trauma wounds seen in whales. Accepted criteria used for diagnosing sharp and blunt trauma will now be applied to evaluate the postmortem findings in these cases.\textsuperscript{8,23,32}

**Overall health and nutritional status**

The nutritional status of the four individuals examined here was qualitatively evaluated postmortem based on the thickness and overall appearance of the blubber layer. Typically, the blubber of a mature, adult female is creamy white in color, opaque, and firm, and, on average, measures 13.93 cm (±2.49 cm SD, N = 32) when measured by using ultrasound on live free-ranging animals.\textsuperscript{1,25} The same study found no significant difference between measurements of excised blubber specimen thickness taken by using an ultrasound probe and those taken with a ruler.\textsuperscript{1}

In the four case study animals, the blubber layer was described as “thick” and “robust” (Eg no. 2150, Eg no. 1004), “measuring 20- to 30-cm along the dorsal midline” (Eg no. 1909), or the animal was categorized as “not emaciated” in the absence of blubber measurements (Eg no. 2143). The blubber appearance was noted as “normal (i.e., creamy white) in color,” and “creamy white” (Eg no. 1909), or was retrospectively determined to be creamy white in color from photographs in the absence of specific commentary (Eg no. 1909). In each case, the animal was found to have sufficient blubber thickness (evaluated at multiple stations according to standard protocol) and appearance, such that the animal was equal to or above the average blubber thickness measured in live free-ranging adult females.\textsuperscript{1} Similarly, all carcasses had moderate-to-marked postmortem autolysis microscopically characterized by the loss of cellular detail and the presence of large bacterial rods. The bacteria were considered postmortem overgrowth or cadaver bacilli and were not thought to have played a role in the death of the animal. As such, in all four cases, compromised nutritional status was not considered a significant factor that contributed to the death of the animal.

**Relative timing of trauma**

It is important, albeit challenging, to distinguish between premortem and postmortem trauma. The characteristics of antemortem, perimortem, and postmortem trauma were considered when analyzing a carcass and interpreting histopathologic findings.\textsuperscript{3,8,12,16} For this analysis, an antemortem lesion was defined as one that occurs more than 6 hours before death, thus allowing sufficient time for the initiation of tissue response. For example, in humans, acute hematoma and coagulation at a fracture site occurs within 6 to 8 hours of the injury and is followed by inflammatory cell localization and differentiation.\textsuperscript{2} These changes are detectable upon gross or histologic examination of fresh samples; however, they may become less evident as tissue quality declines. Evidence of bone healing is relatively resistant to decomposition and is a definitive indicator that an injury occurred 7 to 14 days before death.\textsuperscript{2}

Perimortem lesions are those that occur within 6 hours of death, be it just before or immediately after death.\textsuperscript{2} Postmortem lesions occur after the death of the animal and generally lack evidence of tissue reaction, particularly with increased time between death and injury. Distinguishing between antemortem and postmortem processes is not always a simple task.\textsuperscript{8,12,32} Cases that lack definitive evidence of antemortem or postmortem injury are conservatively classified as perimortem. Characteristics and examples of relevant antemortem, perimortem, and postmortem bone pathology are shown in Table 2.\textsuperscript{12,24} Carcasses that display evidence of perimortem bone fracture co-occurring with extensive subdermal edema and hemorrhage are believed to result from blunt trauma attributed to vessel-whale collisions.

It is particularly difficult to distinguish between perimortem and postmortem fractures without forensic necropsy records that detail the direct examination of accompanying soft tissue.\textsuperscript{32} Histologic examination that reveals inflammatory response is sufficient to determine that the wounds occurred before death.\textsuperscript{32} Histologic examination may also be used to determine if fractures may have occurred in bone weakened by preexisting pathologic processes.\textsuperscript{12} Indirect evidence may also be used to establish timing of trauma. Right whale carcasses at sea are typically found floating with either the ventral or the lateral midline facing upward, at or above the sea surface.\textsuperscript{35} As such, injuries to the dorsum are taken as indirect evidence of premortem or perimortem trauma. This indirect evidence is particularly useful in support of (or in the absence of) direct evidence of the relative timing of trauma.

**Sharp trauma**

The three categories of sharp trauma are stab wounds, incised wounds, and chop wounds.\textsuperscript{8} Stab wounds, once common in the whaling era, are now rarely found, given the ban on harvesting right whales. The depth of a stab wound is characteristically much greater than its length and thereby provides important clues regarding the size and shape.
Table 2. Definition and appearance of antemortem, perimortem, and postmortem bone pathology of a traumatic origin.

<table>
<thead>
<tr>
<th>Timing of pathology</th>
<th>Antemortem</th>
<th>Perimortem</th>
<th>Postmortem</th>
</tr>
</thead>
<tbody>
<tr>
<td>Examples</td>
<td>Healed or healing fractures</td>
<td>Unhealed fractures noticed during necropsy.</td>
<td>Unhealed fractures from postmortem vessel strike, surf trauma, machinery during necropsy, damage in storage.</td>
</tr>
<tr>
<td></td>
<td>Osteoarthritis</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pitting</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Accretion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Characteristics</td>
<td>Abnormal density or morphology, possible asymmetry when comparing paired bones. Organizing and organized hematoma.</td>
<td>Obvious lack of complete healing. Often accompanied by soft tissue edema and hemorrhage. Unorganized coagulation.</td>
<td>Specific detail in necropsy report that no fractures were evident in bones examined.</td>
</tr>
<tr>
<td>Fracture margins</td>
<td>Potential osteoblast repair (smoothing or rounding at margin) with some postfracture survival.</td>
<td>Irregular margins.</td>
<td>Jagged, linear, or squared edges, and splintering, particularly seen when dry bone is broken.</td>
</tr>
<tr>
<td>Signs of healing</td>
<td>Variable depending on postfracture survival (nonunion, malunion, or angulation may be apparent). Increased density of remodeled bone is visible radiographically in adult humans.</td>
<td>Absent</td>
<td>Absent</td>
</tr>
<tr>
<td>Presence of callus</td>
<td>Callus apparent if fracture is recent. Variable presence of fibrous or bony callus depending on postfracture survival time.</td>
<td>Absent</td>
<td>Absent</td>
</tr>
<tr>
<td>Soft tissue appearance</td>
<td>Potential edema or hemorrhage with recent actively healing fracture.</td>
<td>Associated edema or hemorrhage. Histologic evidence of inflammatory response.</td>
<td>No hemorrhage, though postmortem processes resembling “bruising” are known.</td>
</tr>
</tbody>
</table>

of the penetrating object. A recent source of stab wounds is the implantable tag, a subdermal transmitter used by researchers to track whales. None of the four animals examined had been tagged.20

Incised wounds occur when a body comes into contact with a sharp-edged object. These wounds have characteristically smooth, straight edges, and the length of the wound is generally much greater than its depth.8 There are no abrasions or contusions associated with incised wounds, and the tissue is cut clean through to the base of the wound.21,31

The length and depth of an incised wound provide few clues as to what type of object created it.8

Chop wounds are seen when a relatively heavy object, with a cutting edge, contacts soft tissue and, often, underlying bone.31 These wounds are typically incised but often have some characteristics of a laceration (a blunt trauma injury defined below). As with incised wounds, the depth of the wound may vary and present as relatively superficial at the margins, deepening toward the center of the wound. Unlike incisions, tissue bridging (remnants of soft tissue connecting opposing margins of the wound) and hemorrhage may be observed, and the morphology of a chop wound may provide significant clues as to the object that created it.8

When boat propellers contact soft tissue, they create a chop wound in the form of a series of more or less parallel, curved, evenly spaced s-shaped or z-shaped gashes that are often deeper in the center than at the margins.8,23 The angle to the line of travel and the shape, spacing, depth, and length of cuts provide evidence of the rotation and approximate diameter and pitch of the screw, although the number of blades has to be assumed. Propeller trauma is usually acute and ranges in severity from mild, superficial epidermal wounds to more severe damage to the underlying blubber, muscle, viscera, and
bone, and complete dismemberment. Histologic analysis may provide evidence of hemorrhage or repair, a definitive feature of antemortem trauma.

Wounds or scars from propeller trauma were documented in both dead and living right whales. Fifteen of the 71 right whale mortalities (21.1%) since 1970 displayed wounds consistent with propeller trauma. Because forensic necropsy is presently the only method that permits other causes of mortality to be ruled out, a more conservative estimate would eliminate mortality cases that were not necropsied, despite the presence of “propeller gashes.” Thus, of the 40 necropsied carcasses, 11 (27.5%) were fatalities that resulted from vessel-whale collision as an etiology for fluke amputation via laceration. As such, future cases that display a similar wound pattern without anecdotal evidence may be interpreted in light of the precedent set by this case and conservatively classified as a “possible ship strike.”

A few notable individuals survived the acute vascular and tissue trauma caused by fluke damage (Fig. 1a). Damage to small peripheral vessels and distal fluke tissue may not be as lethal as trauma to the proximal flukes and the peduncle. Involvement of large-bore vessels may lead to rapid loss of blood volume from an open wound (as indicated in two independent reports of Eg no. 1909 bleeding after collision with a vessel) or disruption of caudal circulation if the vessel is constricted (as seen in severe entanglement). Thus, it seems that the severity of the trauma (depth, length, and surface area involved) as well as the anatomical location of the wound are important in determining the immediate lethality of sharp trauma injury, whereas chronic sequelae from infection, improper healing, or reduced function may prove lethal in a far less predictable manner.

Blunt trauma

Mechanical stress applied to a body causes blunt force trauma. To cause a blunt force injury, stress applied to the tissue must be great enough to deform the elastic or viscoelastic tissue beyond its ability to recover or maintain integrity. This can occur in situations where 1) the magnitude of the applied stress is greater than the ultimate strength of the tissue; 2) the stress is imparted in an unnatural direction, loading the tissue in a direction with weaker material properties; or 3) the stress is applied to mechanically inferior pathologic tissue.

From a biomechanics perspective, the severity of the injury is dependent upon many factors, including the magnitude of the force, the area across which it is applied, the angle of contact, tissue elasticity and plasticity, and the contact time, which together influence the amount of energy transferred to the animal. A first-order estimate of the ultimate strength (σull) can be found by using the equation

\[ \sigma_{ul} = \frac{F}{A_t} \]
where \( F \) is the load at failure and \( A_i \) is the initial cross-sectional area of the tissue. Thus, even a relatively small force applied over a very small area can result in severe injury.

In general, blunt force injuries are classified into four categories: 1) abrasions, 2) lacerations, 3) contusions, and 4) skeletal fractures.\(^{5,9}\) Anecdotal and forensic evidence of all four categories of blunt trauma were established in dead or living right whales.\(^{17,18,22,30}\) Abrasions are produced as a result of friction that leads to scraping or scuffing of the epidermis. Abrasions are often seen on the epidermis of right whale carcasses; however, they are generally superficial and of unknown origin. A series of equally spaced, parallel, superficial abrasions may be taken as evidence of tooth-mark scars from predators or scavengers. Lacerations are tears or fissures in the tissue caused by shear stresses and stretching forces across a tissue plane (see Case study II, Fig. 5). Lacerations are more likely to occur in tissue superficial to bone than in tissue overlying additional soft-tissue layers. Typically, lacerations have irregular margins and tissue bridging when select intact remnants of more resilient tissue (e.g., vessels and nerves) traverse the wound.\(^{8,21,31}\)

The margins of a laceration are typically associated with hemorrhage.\(^{21}\) Contusions are bruises or areas of soft tissue hemorrhage. They result when an applied stress causes blood vessels to rupture, releasing blood into surrounding tissues. Hematoma can follow tissue hemorrhage (see case studies III and IV, and Figs. 6, 7, and 10). Skeletal fractures occur when bones break in response to mechanical stress. In right whales hit by vessels, it is common to find fractures in the mandibles, cranium, rostrum, or vomer; disarticulated vertebrae; and tympanic bullae (see case studies III and IV, and Fig. 9).\(^{5,30}\)

The number of fatal versus nonfatal vessel-whale collisions that occur each year is unknown. Unlike vessel collisions that involve sharp trauma from propeller damage, nonfatal interactions between a whale and the hull of a vessel leave little immediate or lasting external evidence. Because forensic necropsy is presently the only reliable method that both exposes externally obscure evidence of blunt trauma and permits other causes of mortality to be investigated, a conservative estimate would consider only those animals that were thoroughly necropsied. Thus, of the 40 necropsied carcasses, 9 (22.5\%) were fatalities that resulted from blunt trauma.\(^{17,26,30}\)

The necropsy findings from Eg no. 1004 revealed extensive hemorrhage and edema, which suggests widespread contact with an object before death (Fig. 7). The laceration to the oral rete occurred before death, as evidenced by the blood-spray pattern on the lingual surface of baleen and the roof of the mouth. This would not have been apparent if it was indeed a postmortem injury. Histologic analysis of the broken rostrum revealed irregular bone margins and no signs of healing in the form of woven bone. Both of these findings are consistent with a perimortem fracture induced by blunt trauma.

In the case of Eg no. 2150, the substantial black tarry substance found in the thoracic cavity provided evidence of trauma and blood loss into this region. Similarly, the hemorrhage found overlying the fractured left vomer, around disarticulated ribs, and in soft tissue surrounding the fractured mandible also implicated a perimortem vessel-whale collision event. However, histologic analysis of the fracture plane of the right mandible revealed the presence of necrotic and woven bone, as well as cartilaginous tissue, indicative of a healing process that occurred at least several days before death. Gross examination and computed tomography revealed an area of pitted bone that flanked both sides of the fracture plane and extended a total length of approximately 45 mm, consistent with histologic findings of necrosis.

There are two possible interpretations of these findings. The woven bone may be taken as a sign that the animal survived for a period of days to weeks after an initial vessel-whale collision that caused the mandibular fracture. This would lead to the conclusion that a second collision resulted in the massive skull fracture that involved the brain case. Alternately, healing, indicated by the presence of woven bone, may have preceded the fracture, where bone disease in the right mandible may have predisposed the area to fracture when the animal was hit by a single vessel, resulting in all of the perimortem fractures and bruising found upon necropsy. Although neither interpretation is exceptionally parsimonious, both implicate a vessel-whale collision event as the underlying cause of mortality. Further analysis of the pathologic region of bone surrounding the fracture plane may improve diagnostic conclusions.

**CONCLUSIONS**

The documentation of the number of deaths and the sources of mortality in the highly endangered right whale population is a main goal of right whale biologists and managers. The characterization of deaths that result from human interactions, including vessel-whale collision events and entanglement in fishing gear, provides valuable statistics to those
agencies responsible for right whale protection. The direct classification of wounds and the identification of indicators of disease process or human interaction are essential for future necropsies, accurate diagnoses, and precise mortality statistics.

Here, four carcasses were examined and classified by comparing the type of tissue damage identified during forensic necropsy to the diagnostic characteristics of sharp and blunt trauma. These cases present evidence of traumatic and ultimately lethal encounters between vessels and whales. This study does not include all of the right whales that died or were necropsied during this time; however, in their thoroughness and rigor, these cases are representative of forensic necropsy results reported over the past decade.26

A critical assessment of these cases proves that forensic necropsy remains the key to determining the cause of death. This is particularly important in cases of whales that sustain blunt force injuries, because external evidence of internal trauma is generally minimal. The importance of documenting injuries seen during necropsy of animals acedentially tied to a ship strike is clear upon review of case study II. The observed trauma (i.e., avulsion of the left fluke via laceration) had not been previously associated with a vessel-whale collision. This case sets a precedent for future cases where similar injuries are seen in the absence of anecdotal evidence of a collision. The classification of these cases provides an effective field standard to which future forensic necropsy cases can be compared for the appropriate characterization of traumatic injury suites typically encountered during right whale necropsy.

Because more than half (52.5%) of the 40 right whales necropsied to date displayed evidence of vessel-whale collision trauma, and additional right whales that were not necropsied showed signs of serious injury and scarring from encounters with vessels, reducing the occurrence or lethality of vessel-whale collisions was identified as a key component in the management plan by the National Oceanic and Atmospheric Administration Fisheries.14,18,28 Efforts to mitigate vessel-whale collisions by implementing coastal speed restrictions and routing changes in right whale critical habitat and migratory corridors in the United States are being considered.29,36 Past efforts, including the rerouting of shipping channels to avoid right whale feeding grounds between New Brunswick and Nova Scotia, and two Mandatory Ship Reporting Systems are presently being evaluated for efficacy.

Furthermore, studies that rely on samples obtained during necropsy are vital to ongoing research regarding vessel-whale interactions. For example, the extraction of the tympanic bullae and subsequent computed tomography imaging has provided insight into the auditory range and ability of right whales to detect vessel noise.34 In addition, necropsy records indicate that the right whale mandible has been fractured in a third of the cases that displayed evidence of blunt trauma because of vessel collisions, yet healed mandibular fractures have never before been seen in right whale skeletal remains.35 As such, a mandibular fracture represents an appropriate fatal end point for vessel-whale collision modeling. Material property analyses of mandibular bone and soft tissue overlying the right whale mandible will be used to model the stresses capable of fracturing right whale bone.4 When combined with potential stresses presented by vessels traveling at a given speed, speed restrictions may be evaluated as a means of reducing vessel-whale collision fatalities. The aforementioned studies, along with data obtained from future necropsies and the appropriate characterization of trauma findings will continue to inform ongoing efforts to reduce vessel-whale collision mortalities.

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