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Occurrence of Pulmonary Arteritis with Lungworm Infections in Gray Seals from New England, 2013-2020

Jillian Broadhurst and Inga Sidor, DVM, MS, DACVP

Introduction

The gray seal (*Halichoerus grypus*) is a common pinniped species of North Atlantic coastal waters (NOAA, n.d.). Three defined stocks exist including the western North Atlantic stock ranging from eastern Canada to the northeastern United States, the eastern North Atlantic stock encompassing Great Britain, Iceland, Norway, Denmark, Russia, and the Faroe Islands, and the Baltic Sea stock (NOAA, n.d.). Across their geographic range, conservation efforts have been implemented successfully and general population increases are being observed, especially within their southernmost regions of southwestern Nova Scotia and the eastern U.S. (Bowen, 2016; Heyer et al., 2020). In 2016, surveys estimated pup production in the northwestern Atlantic to be roughly 109,000 pups (Heyer et al., 2020). The western North Atlantic population, whose members are the largest on average (Bowen, 2016), is protected by the Marine Mammal Protection Act in the U.S. Consequently, regular population census counts are performed and some colonies have been recently established or reestablished as a result of these efforts, including Green Island, Seal Island, Monomoy Island and Muskeget Island (Bowen, 2016; Heyer et al., 2020; Wood et al., 2019). Significant population spikes have been observed in recent years especially within the species' southernmost ranges, including those in the northeastern U.S. at the focus of this study (Heyer et al., 2020). Following total extirpation in the United States in the early to mid-20th century due to hunting, several U.S. breeding colonies

have experienced dramatic rebounds: in a study observing trends from 1988 to 2019, the number of pups on Monomoy and Muskeget Islands off the coast of Massachusetts increased at rates of 26.3% per year and 12.8% per year, respectively (Wood et al., 2019). Muskeget Island was named the third largest breeding colony within the northwestern Atlantic gray seal range, producing about 3,900 pups (Heyer et al., 2020). As of 2016, estimates calculated 6,500 pups in the U.S. breeding colonies within Massachusetts and Maine (Heyer et al., 2020).

Gray seals are long-lived and employ a slow offspring production reproductive strategy. Females reach maturation around age 4, where they begin an annual breeding cycle and produce one pup following an 11-month gestation (Heyer et al., 2020; Bowen et al. 2006; NOAA, n.d.). Females in the western North Atlantic stock typically give birth in the months of December to January, with births taking place on land or sea ice (Heyer et al., 2020; Bowen et al. 2006; NOAA, n.d.). The lactation and weaning process is brief, with lactation lasting just two to three weeks, after which the mothers leave their offspring (Bowen et al., 2006; NOAA, n.d.). Breeding can continue for decades, with their average lifespan being 30 to 40 years (Bowen et al., 2006; NOAA, n.d.).

The gray seal is a generalist that consumes a wide-ranging diet, including sand eels, cod, flatfish, pollock and flounder species (Bowen, 2016). In North Atlantic waters, these species may include sand lances (*Ammodytidae*), whiting (*Merlangius merlangus*), redfish (*Sciaenops ocellatus*), Atlantic cod (*Gadus morhua*), silver hake (*Merluccius bilinearis*), turbot (*Scophthalmus maximus*), yellowtail (*Seriola lalandi*), and crustaceans, among others (Bowen, 2016; NOAA, n.d.). Along with geographic location, their diet can also vary depending on age class, sex or seasonal food availability (NOAA, n.d.).

The gray seal is prone to several different causes of mortality, including disease, human interference, and predation (Bogomolni et al., 2010) . In stranding events, cause of death is often attributed to a synergy of these factors; however, disease alone can be attributed to a highly significant number of deaths (Bogomolni et al., 2010). In a compilation of stranding events of marine species on Cape Cod over a six-year period, gray seals had human interaction as the leading cause of death with a notable amount of these cases being entanglements; disease followed behind as the second most common diagnosis in cause of death (Bogomolni et al., 2010).

Among the various disease processes involved in gray seal mortalities, parasitic infections are especially prevalent in gray seal populations. Numerous parasites have been recorded as causing severe health problems in marine species (Dailey, 2001), making an understanding of their pathogenesis in marine mammals crucial. The western North Atlantic population comprising the individuals in this study is no exception, and parasitic infection has been commonly recorded in seal mortalities for this region. The same Cape survey cited verminous pneumonia and gastritis as frequently occurring in pinnipeds, and that it was even considered the immediate cause of death in severe cases (Bogomolni et al., 2010).

Seals and other pinniped species have specialized respiratory physiology as a consequence of their reliance on diving for food resources. The basic pleural structure, however, is rather similar to dogs and other canids. Like dogs, gray seals possess two lobes on the left and three on the right (Rommel and Lowenstine, 2001). A key feature of these lungs for marine species in particular is their variance in size, which is directly correlated with diving proficiency (Rommel and Lowenstine, 2001). Those making deep, prolonged dives, as is characteristic of gray seals, have smaller lungs allometrically speaking (Pabst et al., 1999). Some circulatory

structures have also deviated from typical mammalian physiology to accommodate an increased need for thermoregulation and diving. These include the caval sphincter, which can regulate increased flow of oxygenated blood to the heart during dives, as well as numerous countercurrent heat exchangers and arteriovenous anastomoses (Rommel and Lowenstine, 2001). Phocids have also adapted to have bronchi and bronchioles reinforced with cartilaginous tissue for increased strength (Rommel and Lowenstine, 2001) and numerous bronchial glands (Rommel and Lowenstine, 2001) to bolster the efficiency of this system. Another special adaptation for diving consists of myoelastic sphincters within the terminal bronchioles (Rommel and Lowenstine, 2001). These structural and physiological distinctions characteristic of phocid species highlights the importance of respiratory function to the ecology of this group.

With the essential nature of high respiratory function considered, malfunction of this system in particular can be of serious consequence to grey seals. Several respiratory diseases of viral, bacterial and parasitic origin are associated with this species. In 2010, bacterial and verminous pneumonias were frequent findings among pinnipeds in Cape Cod (Bogomolni et al., 2010). Bacterial bronchopneumonia in particular is especially common in stranded pinnipeds, and is often a result of heavy parasitism in stranded marine mammals (Dunn et al., 2001). Viral respiratory diseases include influenza virus, phocine distemper virus, and even canine distemper virus. Finally, a wide variety of parasitic classes including protozoal and helminth species have been implicated in respiratory distress of pinnipeds, notably heartworm disease (Dailey, 2001). Common helminths implicated in respiratory infections of pinnipeds in particular include *Otostrongylus circumlitus*, *Filaroides (Parafilaroides) spp.*, *Acanthocheilonema odendhali*, *Acanthocheilonema spirocauda*, and *Dirofilaria immitis* (Dailey, 2001). Though the lungworm species of *Otostrongylus circumlitus* and *Filaroides (Parafilaroides) spp.* are typically more

common findings in gray seals, it is difficult to differentiate lungworms from other helminth species in diagnosis.

Definitive prevalence reports of many of these parasitic species are scarce in the literature. However, a handful of seal lungworm case reports in some locations do exist. A study examining gray seals that drowned due to entanglements off the coast of Scotland, for example, found that 57% of the animals had a lungworm infection (Baker, 1987). *O. circumlitus* in particular has been identified as having a very widespread distribution across the northern hemisphere (Measures, 2001). In the United States, cases have been reported in New England, Washington, Oregon and California (Measures, 2001). High percentages of the parasite in harbor and elephant seals in U.S. coastal waters have been reported (Gulland et al., 1997; Dailey and Stroud, 1978; Dailey and Otto, 1982), including 34% of 94 harbor seals on New England coastlines (Geraci and St. Aubin, 1979).

The current prevalence of lungworm parasites affecting the respiratory systems of pinnipeds were of particular interest in this study. One of the most frequent pathogens behind seal respiratory infections, *O. circumlitus*, served as the focus of our analysis due to its unique disease process and dramatic resulting lesions garnering increased attention in recent years. *O. circumlitus* is a large nematode parasite of the Crenosomatidae family affecting the respiratory and circulatory systems of pinnipeds (Dailey, 2001). Adult worms are primarily found within the bronchi and bronchioles of affected seals, but are occasionally observed in the heart or pulmonary arteries as well (Measures, 2001). This species can utilize multiple phocid pinniped species as its final host, including grey seals, harbor seals (*Phoca vitulina*), spotted seals (*Phoca largha*), ringed seals (*Pusa hispida*), ribbon seals (*Phoca fasciata*), Baikal seals (*Phoca sibirica*), bearded seals (*Erignathus barbatus*), and northern elephant seals (*Mirounga angustirostris*).

Across these species, significant percentages of animals studied in stranding events over the decades were found to harbor this parasite, with the majority being under one year of age (Measures, 2001).

Despite their profound impact on marine life, there are considerable gaps in understanding of lungworm ecology and transmission among marine populations (Lehnert et al., 2010). The full life cycle of *O. circumlitus* has not been identified, with the full developmental processes occurring in the seal host unknown. It is believed, however, that fish species eaten primarily by weanling seals act as an intermediate host (Dailey, 2001). (Figure 1). Once introduced to the seal, adult worms eventually migrate to lung tissue (Measures, 2001). (Figure 1). In rarer cases these mature worms have also been found in the heart, pulmonary artery, and liver vasculature; some immature forms of the parasite have been observed in the heart and pulmonary artery as well (Measures, 2001, (Menschel et al., 1966; Onderka 1989; Gulland et al., 1997; Bergeron et al., 1997). These findings have led to the hypothesis that following ingestion, larvae travel through hepatic portal vein or pulmonary circulation to the respiratory system, where they eventually mature and reproduce (Figure 1; Figure 2). Adult females then release first-stage larvae into airways where they are commonly observed postmortem (Measures, 2001) (Figure 1; Figure 2). These larvae become lodged in mucus and are subsequently moved up the respiratory tract through mucociliary movement (Measures, 2001). (Figure 2). It is thought that they can then be swallowed and pass into the digestive tract (Figure 2), explaining findings of first-stage larvae also in fecal matter (Measures, 2001). This then allows for entry of the larvae back into the external environment (Figure 1).

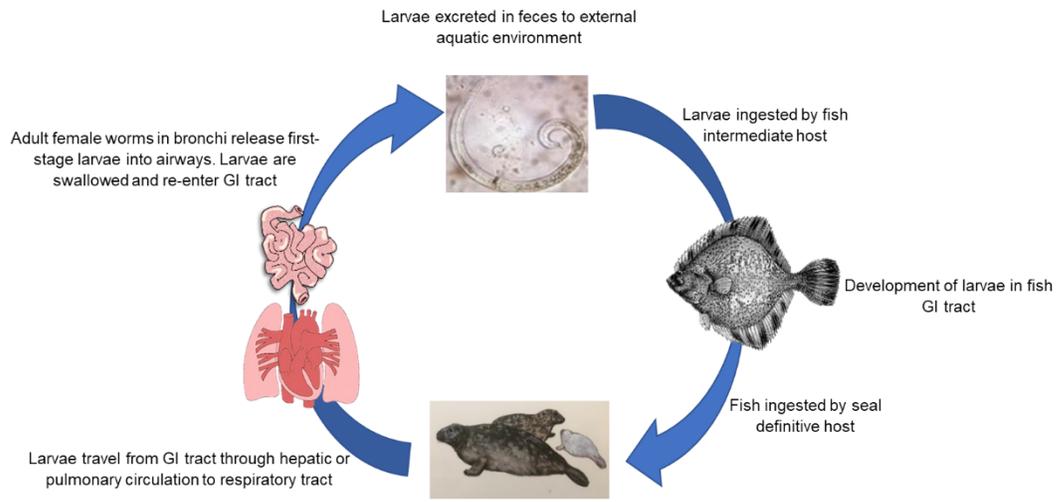


Figure 1. Tentative life cycle diagram of the *Otostrongylus circumlitus* parasite.

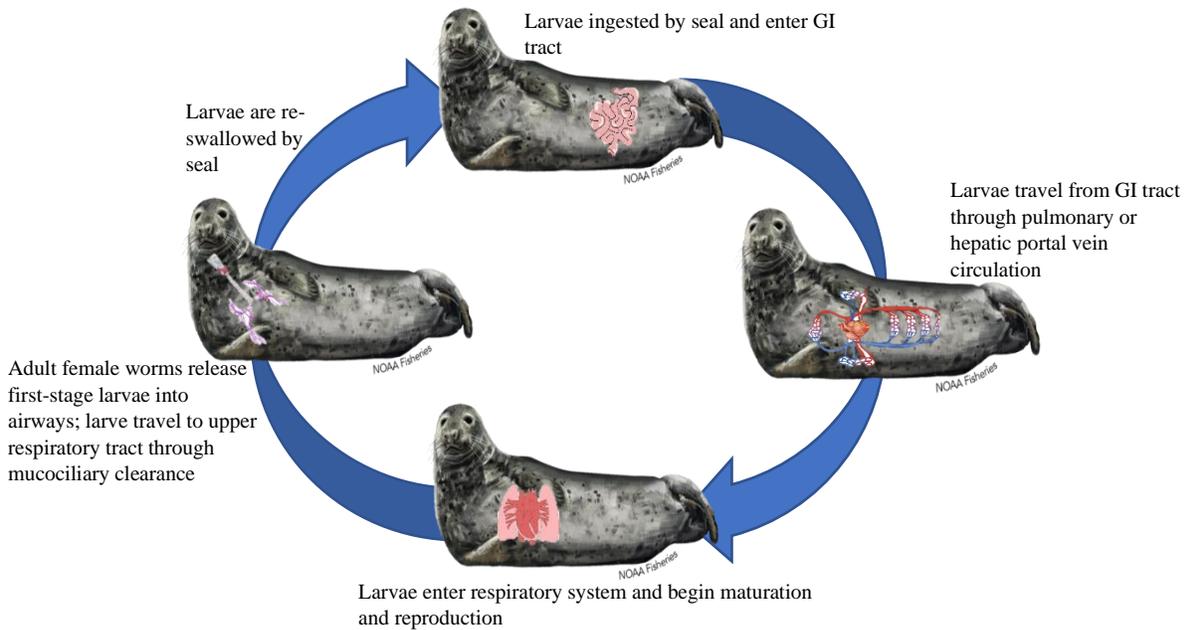


Figure 2. Tentative diagram of the movement of the *Otostrongylus circumlitus* parasite through the body of the gray seal.

While the particular fish species have yet to be identified, it is thought that fish consumed by the seal act as an obligate intermediate host for the lungworm. The intermediate host has not been observed within its natural environment, but some studies have conducted successful experimental infections of fish species. Lehnert *et al.* orally exposed 18 captive turbot fish to live first-stage (L1) *O. circumlitus* larvae and portions of uteri containing eggs and L1s taken from adult females found in harbor seals at necropsy. Forty percent of the fish were later found to have L2 and L3 larvae infections within the intestinal wall, suggesting that these flatfish are a likely intermediate host (Lehnert et al., 2010). Similarly, Bergeron *et al.* experimentally infected several fish, mollusks, and crustaceans with *O. circumlitus* L1s dissected from juvenile ringed seals. They observed a high success rate in the American plaice (*Hippoglossoides platessoides*), observing the majority to possess L3s and providing evidence to implicate this species as an intermediate host as well (Bergeron et al., 1997). Though a true natural host has yet to be identified, the literature has proposed likely species involved in *O. circumlitus* transmission.

Host response to *O. circumlitus* can vary significantly depending on the species and parasitic load, with reports of no inflammatory reactions in some phocids (Munro et al., 1992) and high mortality in others (Gulland et al., 1997). As a target of the respiratory system, diving ability is compromised as a result of this infection. Cases reported are most commonly in young and weanling seals (Measures, 2001). Signs and microscopic findings are widely variable; our cases included several different indications of respiratory distress. Intravascular nematodes can also be associated with vascular damage. Measures 2001 describes historical cases of verminous arteritis within other related marine species including elephant and ringed seals (Measures, 2001; Onderka, 1989; Gulland et al., 1997); however, pulmonary arteritis had not been historically described in grey seals. Recent evidence, however, suggests a possible increase in *O. circumlitus*

respiratory infection among gray seals that includes arterial vasculitis lesions with deposition of Splendore-Hoeppli tissue, a dramatic localized immune response which includes infiltrates of eosinophils, antigen-antibody complexes and tissue debris. Barnett *et al.* recently described the first cases of verminous pulmonary vasculitis and Splendore-Hoeppli material deposition within vessels of stranded and captive U.K. gray seals. We aim to add to these discoveries by describing and documenting the number of similar cases of histopathological changes in the gray seal western North Atlantic stock in New England coastal waters.

Methods

Thirty-three wild, stranded gray seals were included in this study, representing submissions from 2013-2020 from Massachusetts, New Hampshire, Connecticut and Maine coastlines, with the majority in the Cape Cod region. Following stranding events, gross postmortem examinations were conducted by NOAA/NMFS-designated local marine mammal rescue agencies or at the New Hampshire Veterinary Diagnostic Laboratory (NHVDL). Contributing organizations included the International Fund for Animal Welfare (IFAW), the National Marine Life Center (NMLC), Mystic Aquarium Animal Rescue Program, Seacoast Science Center (SSC), and Marine Mammals of Maine (MME). For necropsies performed off-site, formalin-fixed tissue samples and gross necropsy reports were forwarded to the NHVDL for histologic examination. Diagnoses and potential causes of death based on gross and histologic findings were compiled into a database in Microsoft Excel. Only cases with complete gross and histologic findings were included, excluding biopsies or partial submissions not including lung tissue.

Data points recorded for each animal (where available) included its NHVDL identification number, local rescue agency identification number, age in years, age in months,

age class, sex, weight (kilograms), length (centimeters), location of stranding, date found, date of necropsy, history, description after necropsy, preliminary diagnoses and comments, final morphologic diagnoses, necropsy conclusions, and comments after histologic examination.

Analysis of gray seal case data was conducted in Microsoft Excel. For those involving lungworm infection, active infections were denoted as having visible worms seen on examination within the pulmonary and circulatory tissue, while prior infections were those with only residual arteritis present and no lungworms.

For the purposes of this study, age classifications were refined using weight categories adapted from Geraci and Lounsbury when weight data was available. The broad age categorizations used were *Pup*, which encompassed neonatal to weanling animals under one year of age and weighing up to 45 kg, *Juvenile*, referring to yearlings/young of the year and subadults weighing 45-100 kg and greater than 1 year of age, and *Adult* for those weighing 100 kg or greater. In the absence of weight data, age classifications were based on estimates made by stranding agencies at the time of collection.

Results

Thirty-three stranded gray seals with full necropsy reports were received by the NHVDL from 2013 to 2020. The cases presented with a variety of gross and histologic signs of respiratory distress, including dyspnea, bloody mucoid oral and nasal discharge, eosinophilic bronchitis/bronchiolitis, suppurative pneumonia, and pulmonary congestion and emphysema with worms in bronchi (Figure 3; Figure 4). Deposition of Splendore-Hoeppli material with infiltrates of eosinophils in arteries was also commonly observed in histologic sections of the vasculature (Figure 5).



Figure 3. Adult *Otostrongylus circumlitos* worms in the bronchi of a juvenile gray seal during gross necropsy. Photo: Inga Sidor

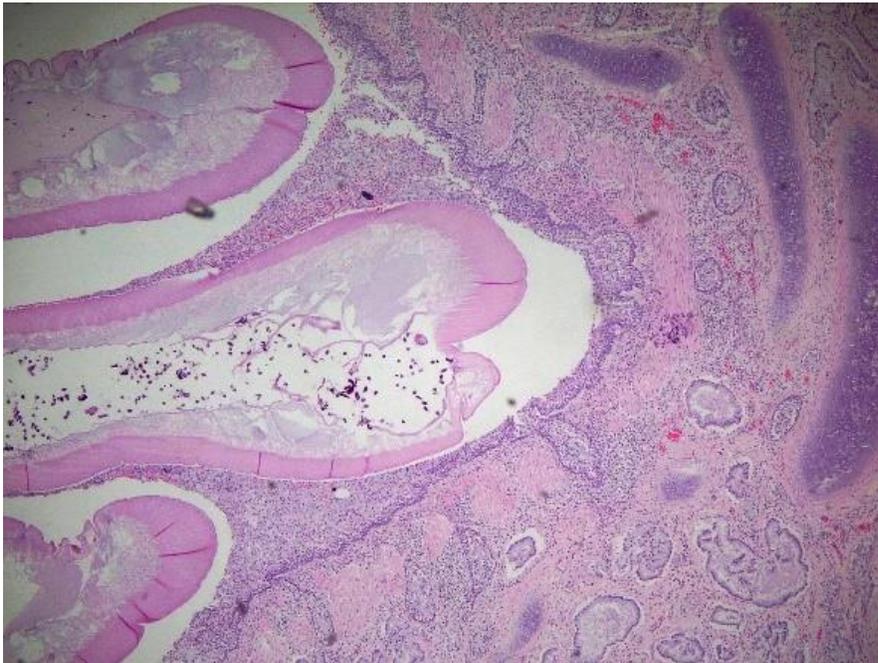


Figure 4. Histologic section of adult *Otostrongylus circumlitos* worms in the bronchi of a juvenile gray seal. Photo: Inga Sidor

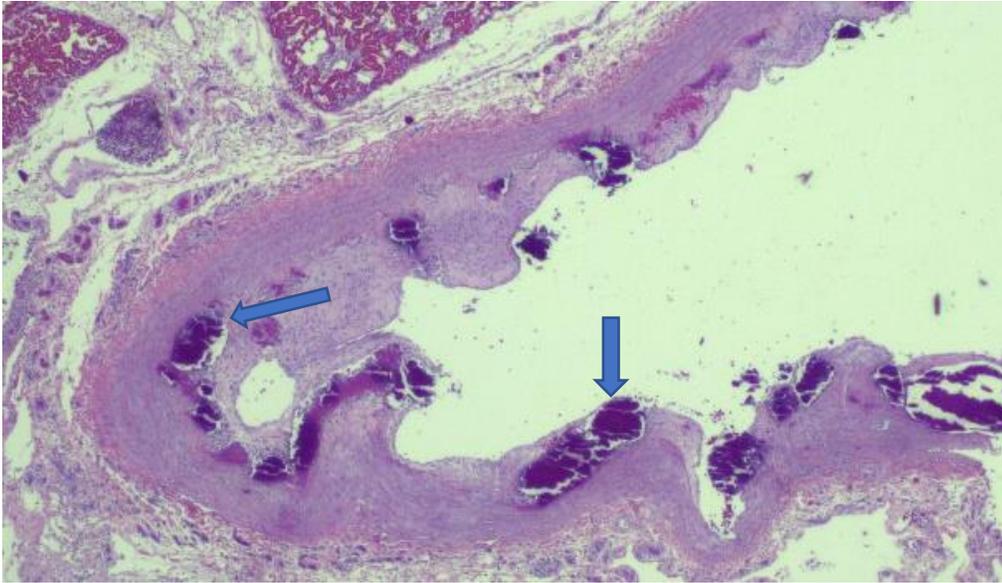


Figure 5. Pulmonary artery from a gray seal (*Halichoerus grypus*) with arteritis. The dark purple material in the arterial wall (see arrows) represent foci of inflammation and deposition of Splendore-Hoeppli material, with irregular thickening of the vascular wall. Photo: Inga Sidor

17 (51.5%) of total cases had evidence of either an active or prior lungworm infection (Figure 6). 14/17 (82.4%) of these lungworm infection cases showed arteritis lesions (Figure 5, Figure 6). 15/17 (88.2%) total active or prior cases were younger animals classified as pups and juveniles. No adults were found to have active lungworm infections, with two having arteritis only and the rest no evidence of active or prior infection (Figure 6). The most stranding events were observed in 2015 and 2018, with 9 and 13 cases, respectively (Figure 7). Over half of the animals in each of these stranding years also had a lungworm infection identified, with 6 in 2015 and 7 in 2018 (Figure 7).

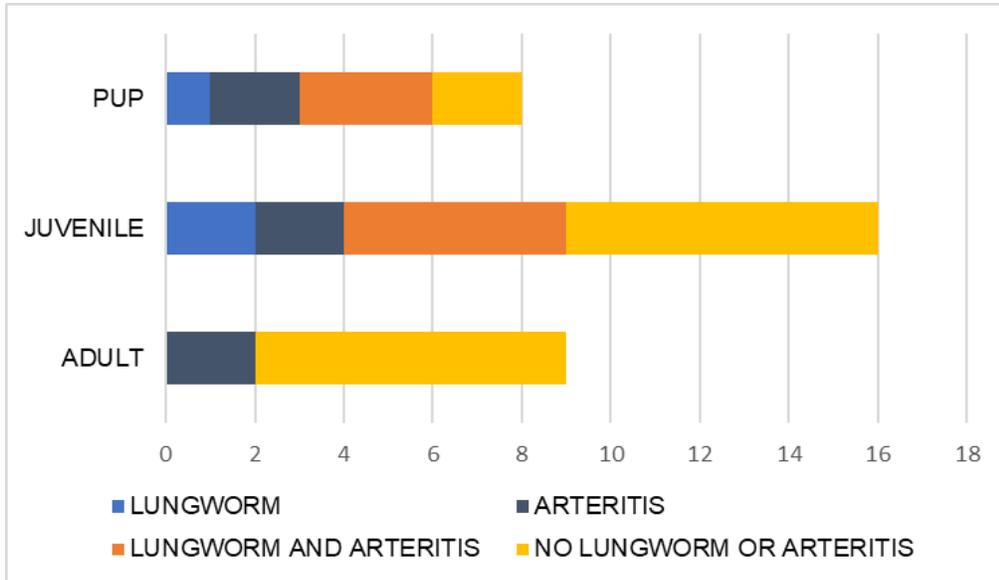


Figure 6. Stranded gray seals from New England, 2013-2020, categorized by age and lungworm infection status.

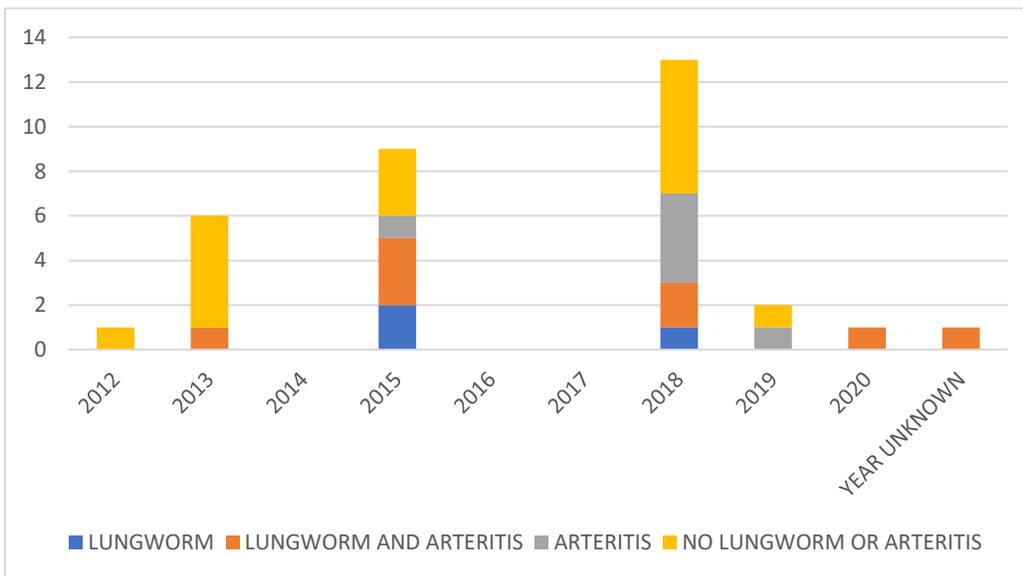


Figure 7. Stranded gray seals from New England, 2012-2020, categorized by year of stranding and lungworm infection status.

Discussion

This study sought to compile gray seal stranding cases and identify the prevalence of *Otostrongylus circumlitus* lungworm infection as well as the presence of arteritis among gray seals in New England coastal waters. Out of the total gray seal deaths, a significant proportion were found to have evidence of verminous pneumonia caused by this nematode, with the majority of these also experiencing arterial inflammation. These findings further underscore the significance of this pathogen in the health of gray seal populations and identify vascular involvement as a prominent complication of the disease. Our findings show that *O. circumlitus* respiratory infection continues to be an important cause of mortality within this population, especially for young animals.

The occurrence of pulmonary arterial lesions is an important finding in support of the recent literature describing this disease process in gray seals. Historically only noted in other phocid species, we expand upon the recent description by Barnett *et al.* of vascular lesions caused by lungworm infection in the eastern North Atlantic stock of gray seals, and show its significant prevalence in the western North Atlantic stock of the species. In a few cases, worms were observed intravascularly, presenting strong evidence of parasitic dissemination from lung tissue to the vasculature as the cause of the arteritis observed. *O. circumlitus* has the potential to severely impact the crucial diving and foraging processes for gray seals, and the marked presence of vascular complications observed could add to this risk.

Additionally, Barnett *et. al* and this study both note cases reaching as far back as 2012 and 2013 respectively, yet in other pinniped species such as the ringed and elephant seal (Measures, 2001; Onderka, 1989; Gulland et al., 1997), arteritis and pulmonary vascular changes due to lungworm infection have been described for decades (Measures, 2001). This begs the

question of whether there may be a greater prevalence for gray seals than there was previously. The frequency of the vascular lesion in these studies and its absence in the historical literature suggests an increase in cases of lungworm with concurrent arteritis, and a sharp increase in a matter of a mere decade at that. If so, it must be asked why these cases were only noted in recent years. The emergence of this syndrome may be attributed to several factors, including a simple reflection of the overall population spikes of gray seals, or even ecosystem structural changes. We hypothesize that increases in prevalence of the undetermined intermediate *O. circumlitus* fish host species, or shifting food availabilities and diet preferences of gray seals, likely due to climate change impacts, may also be playing a role. The increasing gray seal populations themselves may be allowing for increased success of the parasite.

Alternatively, potential evolution of the *O. circumlitus* parasite, or a weakened ability of seal hosts to respond to infection due to physiological impacts of climate change are other possibilities. Gray seals are cold-adapted, living comfortably in below freezing air and water temperatures, and are much less tolerable of heat (Dailey, 2001). As ocean temperatures continue to rise, seals may be experiencing new complications such degraded immune responses. The literature suggests that *O. circumlitus* possesses a differential impact on various seal host species, with the severity of infection depending partly upon host susceptibility (Measures 2001). Munroe *et al.*, for instance, reported bronchial inflammation in harbor seals, but they did not observe inflammatory processes in those with the parasite in pulmonary arteries. It is possible that this was once the case in gray seals as well, but that they have become more poorly adapted to this parasite.

The discrepancies observed in disease severity as correlated with seal ages is also of note. Younger animals were clearly overrepresented, concurring with previous occurrence data in the

literature (Measures, 2001). Only two adults showed evidence of lungworm infection, and both possessed only arteritis without intra-airway lungworms. This evidences a prior lungworm infection that had been cleared but left behind pulmonary arteritis. Conversely, it was more common in pups and juveniles to have an active lungworm infection along with their arteritis. Adult seals may therefore be at a greater capacity to clear their infections than young, who are likely immunocompromised and at greater risk of mortality due to lungworm infection. It has also been proposed that less mortalities are observed in older seals due to their larger bronchial airways that can better facilitate mucociliary clearance (Measures, 2001; Dungworth, 1985). Alternatively, the lack of adult lungworm cases could suggest that undocumented mortalities from the infection have occurred, or that the disease is more difficult to detect by diagnosticians during necropsy in adults.

While gray seal aging techniques have long been used and refined by marine biologists with weight determination as a widely accepted indicator, it must still be acknowledged that our age classifications were only rough estimates. Some individuals may have deviated from the typical weight standards for their age, thus potentially skewing results. Additionally, weights and other demographic information were not available for every individual in this study. In those cases, we had to rely on age classifications determined by the local rescue agency with no further information.

Conclusions

Lungworm infections due to the *O. circumlitus* parasite remain an important contributor to health decline and mortality events for gray seals in New England. We have here identified a significant portion of pulmonary arterial lesions due to this disease in the region, adding to the body of evidence suggesting the possible emergence of an abnormal lungworm pathogenesis in

gray seals due to *O. circumlitus*. In conjunction with findings in other regions, this first report of arteritis due to lungworm infection in New England's gray seals reveals a potentially extensive occurrence of this significant pathogenesis across multiple subpopulations. The impacts of *O. circumlitus* upon the life-sustaining and ecological processes of gray seals, especially in young offspring, render it an important consideration in the monitoring of the species. With the implementation of conservation initiatives boosting the size of the western North Atlantic stock in the US, continued observation of *O. circumlitus* lungworm infection prevalence and a greater understanding of its life cycle and pathogenesis is necessary to monitor population health. Additional work may also explore the potential reasons for increases in the prevalence and severity of lungworm infections today.

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Figure 1 Images:

https://www.pngitem.com/middle/iJJoRxm_small-intestine-clipart-png-download-small-intestine-clipart/

O. circumlitus larvae: Dr. James McBain

Seal: Joseph R. Geraci and Valerie J. Lounsbury

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Figure 2 Images:

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