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Capture and Release of Minke Whales Offers New Research Opportunities, Including Measurements of Mysticete Hearing

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Abstract

Knowledge about species-specific hearing is vital to assessing how anthropogenic noise impacts marine mammals. Unfortunately, no empirical audiogram exists for any mysticete whale. We therefore developed a catch-and-release method to assess hearing in a small mysticete, the minke whale (*Balaenoptera acutorostrata*). Stationary lead nets were placed to intercept migratory routes and direct the whales into an ocean basin enclosed by nets and islets, while another net was pulled across the entrance once a whale entered the basin. The minke whales were then slowly corralled into a modified aquaculture pen using a net suspended between two boats. Subsequently, the water volume available to the whales was gradually reduced by raising the pen net by hand until the whales were secured in a "hammock" between the floating pen ring and a raft. From the raft, researchers could access the whales to monitor their health, apply instruments for hearing tests, or perform other research objectives, and then attach tags to monitor the movements and diving behavior of the whale post-release. The method is a slow and controlled procedure, allowing continuous monitoring and quick release of the whales, if needed. In the first three field seasons employing the method, three minke whales were caught for research procedures. Initial hearing measurements using auditory evoked potentials were successfully completed. After release, the whales resumed migration, and dive behavior was considered normal. Our observations demonstrated that minke whales can be guided safely via moored net barriers, corralled into an aquaculture pen, and safely handled for research purposes, before being released back into the wild.

Key Words: baleen whales, live capture, hearing, physiology, dive behavior, tagging, *Balaenoptera acutorostrata*

Introduction

Cetaceans are divided into the toothed whales (odontocetes) and baleen whales (mysticetes) and are distinguished by fundamental differences in functional morphology, sensory physiology, dive adaptations, and feeding behavior (Reynolds & Rommel, 1999). Several odontocete species are kept under human care in aquariums or dedicated research facilities, where, under strong ethical scrutiny, researchers are allowed to collect blood, take tissue biopsies, or attach instruments to study their physiology. Research with odontocetes under human care has increased biological knowledge about these animals and has subsequently led to better management of wild populations. Primarily due to their size, mysticetes are normally not kept under human care and are only briefly held during stranding or entanglement responses. Some movement, behavioral, and physiological data may be acquired by attaching satellite tags to mysticetes (e.g., Kvadsheim et al., 2017; Cade et al., 2023). However, much of our current understanding of mysticete physiology is derived from postmortem examinations (Goldbogen et al., 2015), or extrapolation from odontocetes or pinnipeds (e.g., Fahlman, 2012; Hooker et al., 2012). As a result, the validity of our understanding of mysticete behavior and physiology remains in question—for example, with respect to diving adaptations (Fahlman, 2012; Hooker et al., 2012), hearing (Cranford & Krysl, 2015; Southall et al., 2019), or thermoregulation and energetics (Lavigne et al., 1986).

To date, hearing in mysticetes has been predicted from anatomical models (Houser et al., 2001; Parks et al., 2007; Cranford & Krysl, 2015; Tubelli et al., 2018), the frequency range of mysticete vocalizations (e.g., Schevill & Watkins, 1972; Clark & Johnson, 1984; Thompson et al., 1986; Cummings & Thompson, 1994), and behavioral responses of mysticetes to incidental and intentional noise exposures (e.g., Todd et al., 1992; Goldbogen et al., 2013; Curé et al., 2015; Sivle et al., 2016; Kvadsheim et al., 2017; Frankel & Stein, 2020, Boisseau et al., 2021). Since no empirical measure of hearing range or sensitivity has been made in a mysticete whale outside of an unsuccessful attempt by Ridgway & Carder (2001) to measure the hearing of a stranded gray whale (*Eschrichtius robustus*) calf, direct measurements of mysticete hearing are needed to validate models and inform knowledge gaps identified by scientists (e.g., Southall et al., 2019), marine noise polluters (International Association of Oil and Gas Producers [IOGP], 2018), and noise regulators (National Oceanic and Atmospheric Administration [NOAA], 2018). Since mysticete whales are not kept under human care, and behavioral hearing tests (the most accurate measure of audition) are not possible to perform, the most likely method of directly measuring hearing in a mysticete is through auditory evoked potential (AEP) methods. These methods have been broadly used and validated on odontocete species (e.g., Szymanski et al., 1999; Yuen et al., 2005; Finneran & Houser, 2006; Houser & Finneran, 2006a, 2006b; Finneran et al., 2009; Ruser et al., 2016; Houser et al., 2022), and they have great promise for use in smaller mysticete species. Nevertheless, the method requires that subject animals are temporarily caught and controlled for the hearing tests.

Previous attempts to catch live mysticete whales for scientific purposes have had limited success (Vinje, 2022). In the late 1950s, there was an unsuccessful attempt to capture a minke whale (*Balaenoptera acutorostrata*) calf for an aquarium. The calf was lassoed by the tail and hoisted onboard a research vessel, but it died upon arrival at the aquarium (Norris & Prescott, 1961). Another aquarium succeeded in obtaining three minke whales between 1930 and 1954 (Kimura & Nemoto, 1956). A fishing net between two boats was used to capture the whales, which were then towed ashore. The whales escaped or died after a few weeks, and scientific measurements were limited to recordings of swim behavior and respiration rate (Kimura & Nemoto, 1956). In the 1960s and 1970s, SeaWorld captured two gray whales using a superficial harpoon followed by netting or a tail noose deployed from a fishing vessel (Norris & Gentry, 1974). The first whale died within 2 mo from lung injury and pneumonia caused by the capture technique (Wahrenbrock et al., 1974). The second whale was kept in captivity for a year before it was released (Norris & Gentry, 1974). Respiratory physiology, circulatory physiology, energetics, vocalization, hematology, and feeding behavior were investigated in these two whales (Curran & Asher, 1974; Duffield, 1974; Evans, 1974; Fish et al., 1974; Gilmartin et al., 1974; Leatherwood, 1974; Mattson, 1974; Medway, 1974; Norris & Gentry, 1974; Ray & Schevill, 1974; Smith & Wahrenbrock, 1974; Wahrenbrock et al., 1974; Zettner, 1974), but no direct measurements of hearing were made. Opportunistic scientific use of mysticete whales accidentally trapped in fishing gear (Winn et al., 1979), in natural enclosures (Beamish, 1979), or live stranded (Edds et al., 1993; Priddel & Wheeler, 1998; Reidarson et al., 2001; Sumich, 2001) have occurred, but again no direct measurements of hearing were made. The most recent attempt to intentionally live-catch mysticete whales for research was specifically conducted to collect AEP audiograms. The effort took place in Iceland in 2007 (IOGP, 2022). An international research team used a modified herring purse seine net to entrap minke whales and had a pontoon boat fitted with a stretcher to restrain a caught whale (J. Teilmann [co-author], pers. obs.). Eighty-one minke whales were observed during 11 d at sea, and a capture net was set four times with no successful catch. The nets were too heavy, took too long to set around the whales, and the whales consequently escaped the capture attempts.

Development of a safe and ethically acceptable method to live-catch and temporarily restrain mysticete whales, without compromising animal health and welfare, will not only provide opportunities to measure hearing, but also to study other aspects of mysticete whale biology, including sensory and respiratory physiology, individual vocal behavior, energetics, and instrumentation for behavioral and physiological studies of free-ranging whales. The objective of the effort reported herein was to develop a safe catch-and-release method for minke whales for the principal purpose of obtaining AEP audiograms for this species. Minke AEP hearing tests will provide the first direct measurement of hearing in a mysticete whale, but the catch-and-release method could have broader potential for studying mysticetes in the wild.

Methods

The methods described herein were meant to target adolescent minke whales, partly because of the practical challenges of handling larger animals, but also because AEPs are more difficult to measure in larger animals due to greater distance from the brain to surface electrodes. Minke whales are also an ideal candidate for this method due to their accessibility in Norwegian waters. They arrive along the Norwegian coast for their seasonal feeding migration in April through June, and a relatively high number of younger animals make a detour into Vestfjorden on their way northwards to the rich feeding grounds in the Barents Sea (Christensen & Rørvik, 1981; Heide-Jørgensen et al., 2001). The field site was located off Stamsund in Lofoten (Norway). The site was chosen after numerous interviews with local fishermen about whale presence in this region, as well as prior experience during whale research in the same area (Walløe et al., 1995), during which minke whales were observed travelling westwards along the Lofoten peninsula, close to and between the numerous Lofoten islands (Figure 1). June, which has generally favorable weather conditions and high whale densities, was chosen as the optimal catch period. Catch attempts were made during three field seasons: June 2021, 2022, and 2023.

The Catch-and-Release Site

The catch-and-release site (CARS) contained 1,790 m of medium-meshed (65 to 78 mm mesh size) purse seine nets ranging from the surface to the seafloor at 20 to 55 m water depth. Net depths were adapted to the bathymetry profile of the site. Anchored lead nets were set to intercept the migration route and direct the animals between the two islets of Kvannholmen and Æsøya (Figure 1). On both the west and east sides of these islets, barrier nets blocked the gap between them to form a large basin (280 m long; 160 m wide; 20 to 30 m deep) with a volume of about 1×10^6 m^3. The barrier net blocking the basin's west side (A-net) was anchored to the islets. The barrier nets blocking the basin's east side (B-nets) contained a 40-m wide opening (CARS-door) and was anchored to the islets and to the aquaculture pen (Figure 2). The circular salmon aquaculture pen was 90 m in circumference and contained both inner and outer nets stretching from the surface to the seafloor. Anchored on the south

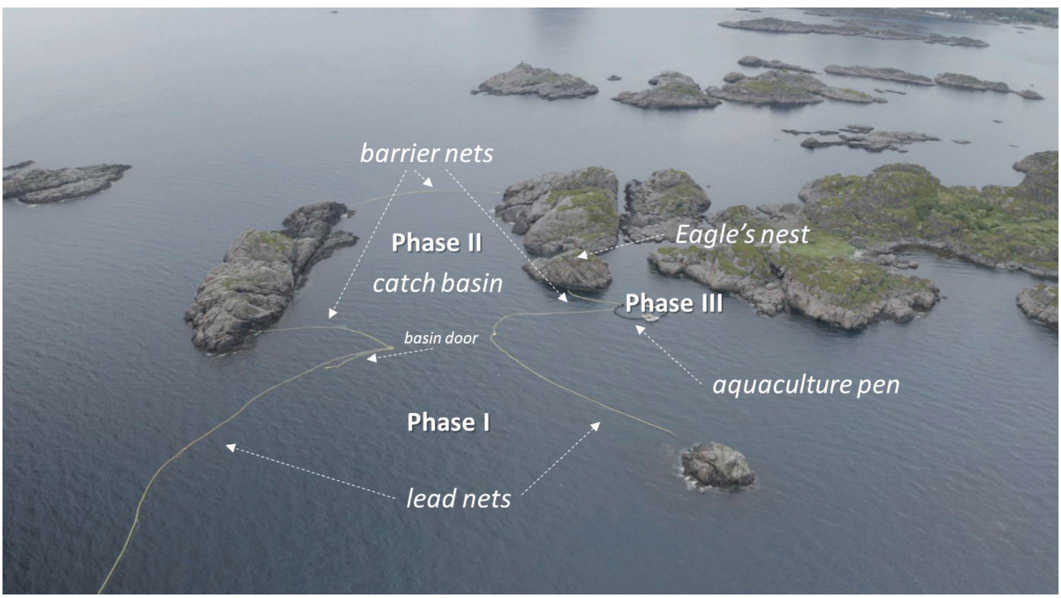

Figure 1. Drone picture of the catch-and-release site. The catch process is divided into three phases: Phase I is the catch phase, which ends when the netted basin door behind the minke whale (*Balaenoptera acutorostrata*) is closed, and the whale is contained in the catch basin; Phase II is the corralling phase, which ends when the door of the aquaculture pen is closed behind the whale; and Phase III is the final phase in which the whale is placed and held in a net hammock, and ends when the whale is released back to the wild. The whales are monitored from the "Eagle's nest" and/or from boats docked at the aquaculture pen from the first sighting in Phase I until the whales were released at the end of Phase III (see Figure 5). (*Photo credit:* E. Wang-Naveen, FFI)

side of the CARS-door, lead nets (D-nets: 1,100 m in length; 45 to 55 m in depth) stretched eastwards to a shallow grounding point (Brusen) where the net was anchored. On the basin's north side opening, a 160-m lead net (C-net: 25 m deep) was anchored and stretched eastwards and attached to another small islet, Ausa (Figure 2). A single unanchored net (E-net: 100 m in length; 20 m in depth) was tethered along the A-net until it was used for corralling a minke whale towards the aquaculture pen. Between field seasons, slight modifications were made to the net configuration (Figure 2). The main adjustment was between years 2 and 3 when the outer part of the D-net (D2) was removed, and the inner part (D1) was bent to the northeast and attached to the islet Flatskjaeret (Figure 2). This modification was based on experiences from the first 2 y to increase the catch rate. When all nets were in place and before catch started, an underwater drone (Blueeye Pro ROV; Blueeye Robotics, https://www.blueyerobotics.com) was used to inspect that the nets went all the way to the rocky and sandy seafloor and that there were no gaps in net junctions.

To provide resilience to tidal and coastal currents in the CARS, all nets were heavily weighted with two bottom lead lines; the main bottom line had 8.4 kg/m weight, and the secondary weight line above it had 2.0 kg/m weight. The top of the net had 28 kg/m of buoyancy (four 7 l buoys/m). The tidal variation is up to 3 m in the area; thus, all barrier nets (A, B1, B2, and B3 in Figure 2) were constructed with a tidal skirt with two weight lines vertically separated by 3 m to reach the bottom at high tide, while allowing them to be held tight without excessive slack at low tide. All nets were constructed with dark nylon netting at Mørenot AS (Ålesund, Norway) from herring and mackerel fishery purse seine nets. The nets were cut into bar meshes before mounting to obtain a stable depth and length and to reduce drag on the nets by allowing water flow through them. The lead and barrier nets were deployed off a large purse seine fishing vessel (> 20 m long) with a triplex net handling system and > 50 m^3 net loading capacity. Several trips were required to deploy all the nets used in the CARS construction (Figure 1). Between years, all nets and lines were stored in

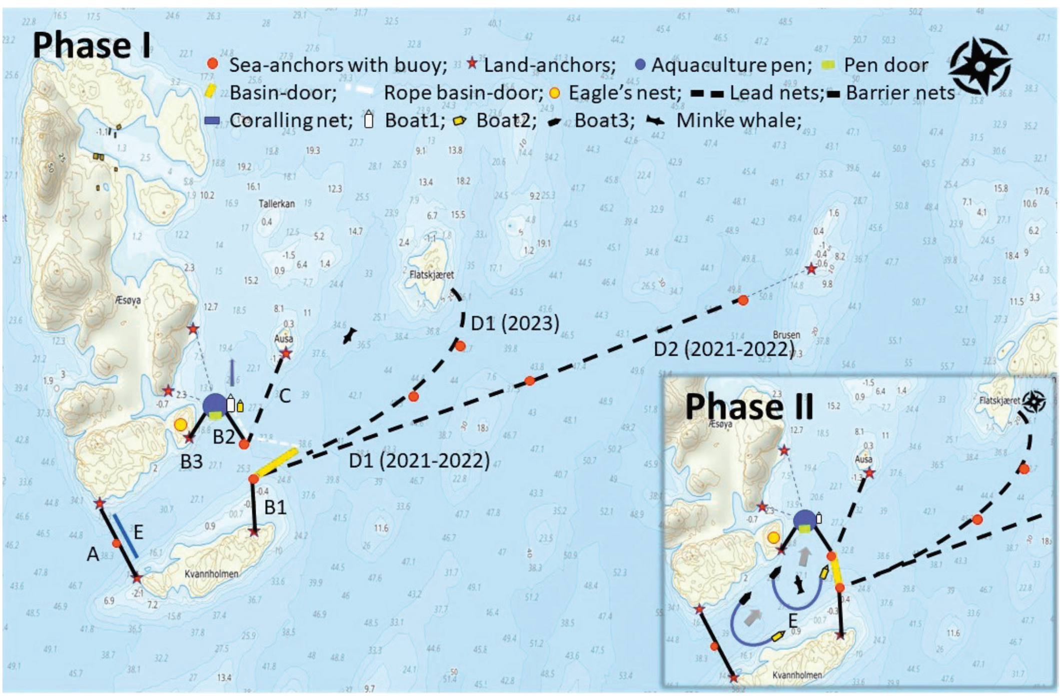

Figure 2. The trap design for live catch and release of minke whales in Lofoten (Norway). The map shows details of the placement of nets (A: 160 m; B1: 120 m, including 40 m trapdoor; B2: 100 m; B3: 50 m; C: 160 m; D1: 600 m; D2: 500 m; and E: 100 m), anchors, 90-m aquaculture pen, observer platforms at the Eagle's nest, and boats (Boat #1 closing the door and Boat #2 patrolling the area). The configuration of the lead nets (C and D) changed somewhat between years (see Figure 4). *Inset:* Map showing the corralling path of a minke whale from the catch basin into the aquaculture pen in Phase II of the catch process. The 100-m-long E-net is pulled between two boats from the A-net eastwards towards the door of the aquaculture pen.

either flexible bulk bags (6 to 8 m^3 capacity) or in 12.2-m steel containers.

The aquaculture pen consisted of double, heavy-duty polyethylene floating pen rings (315 mm diameter) with a stanchion thick-walled (125 mm diameter) handrail. The pen had a buoyancy of more than 10 tons. Two aquaculture nets were used during the catch: (1) outer net with a door constructed in it (10 × 15 m) and (2) an intact inner net without openings. The aquaculture pen nets had a mesh size of 31 mm and were composed of 1.7-mm diameter nylon twine. Top, waterline, bottom, vertical, and horizontal ropes of 18-mm braided Danline were sewn into the nets for structural support, and hooks were mounted into the handrail for attaching excess net during the restraining phase. Each net was made as a cylinder module with a straight wall to 15 m of depth, which was then extended a further 7 m in a coned shape that ended in a weighted center (30 kg). The net had a volume of more than 10,000 m^3. Due to strong tidal currents, the net interiors were weighted with 10 rounded, 30-kg weights suspended from adjustable ropes that were attached to the pen ring. Both aquaculture nets also had 22 vertical ropes tied to the bottom of the net and attached to the top of the ring at even spacing. The ropes were used along with the hooks in the handrail to adjust the depth of the inner net and to tie up the ends of the pen door when open. A raft (8 × 3 m) was constructed to carry four people and the weight of the minke whale in water. It was placed inside the aquaculture pen to be used during handling of the whale in the final phase of the experiment (Figure 3).

Weather was a challenging factor at the field site; thus, the aquaculture pen was anchored to Æsøya so that it was sheltered from the most common wind directions. The aquaculture pen was acquired from a local aquaculture farm (IsQueen AS) and deployed by their 15-m dredger boat. The boat was also hired to adjust barrier and lead nets, and for the deployment of anchor moorings. The floating aquaculture pen ring and nets were secured with strong ropes (30-mm Mixed Dyneema-Polyester) to eyebolts on land at either Æsøya, Kvannholmen, or Ausa (Figure 2), in addition to five 1,200-kg moored anchors (Figure 2).

During minke whale catches, a boat (Boat #1: 8.8-m Halco Offshore with a Volvo Penta 250 HP engine) was docked facing northward at the aquaculture pen. A 200-m-long braided rope (18 mm) was attached to the stern of the boat with the opposite end attached to the CARS-door (Figure 2). The rope was dark colored and sank to the bottom of the ocean floor to avoid being perceived by the whales. A second boat (Boat #2: a 4.9-m fiberglass boat with an outboard four-stroke 90 HP engine) stayed either docked at the aquaculture pen next to Boat #1 or patrolled the catch area, depending on the situation and the weather.

The Catch Process

The catch process was divided into three phases (Figure 1): Phase I – catching the minke whale in the basin; Phase II – observing and corralling the minke whale into the aquaculture pen; and Phase III – restraining the minke whale for instrumentation and experimentation.

Phase I: Catching the Minke Whale—During June, northern Norway experiences 24 h of sunlight, and the CARS was monitored for 20 h of the day using a crew of 12 people (two 10-hour shifts with six people per shift). When the weather condition was too bad to catch minke whales safely, the full team did not go out, but the nets were still checked every 3 h. During each shift, whale lookouts were stationed at an observation point on a hill located on Æsøya (Eagle's nest: 18 m height) and from the boats anchored at the pen ring. Sighted minke whales were visually tracked until they entered the catch basin or left the area. Respiration rates were recorded for all of the whales, and swimming behaviors were scored as either calm and normal swimming (CNS), fast vigorous swimming with porpoising (FVS), or spy hopping (SPY). The CARS was divided into eight zones (0 to 7), primarily to be able to quickly communicate sighting positions (Figure 4; Table 1). As soon as a minke whale was sighted in the catch basin (Zone 0), all personnel were alerted via hand-held radio to close the entrance. Boat #1 then immediately motored northward, pulling on the line to close the catch basin door. Once shut, the crew on Boat #2 secured the net door in the closed position with a line and quick-release carabiners.

Phase II: Observation and Corralling of a Minke Whale into the Aquaculture Pen—After successful containment of a minke whale in the catch basin, its swim behavior and respiration rate were monitored from Eagle's nest (see Figure 2) for a minimum of 2 h in 10-min intervals. If the whale behaved normally (based on pre-capture behavior), appeared healthy (based on body condition and appearance), and the weather forecast for the next 12 h was acceptable, the corralling process was started. During corralling, the swim behavior and respiration rate were monitored continuously.

Before corralling was initiated, the entire inner aquaculture pen net was lowered to the seafloor, and the door in the outer net of the pen was opened and tied to the floating ring. The 100-m-long E-net was then released from its attachments on the A-net and pulled between two small boats (Boats #2

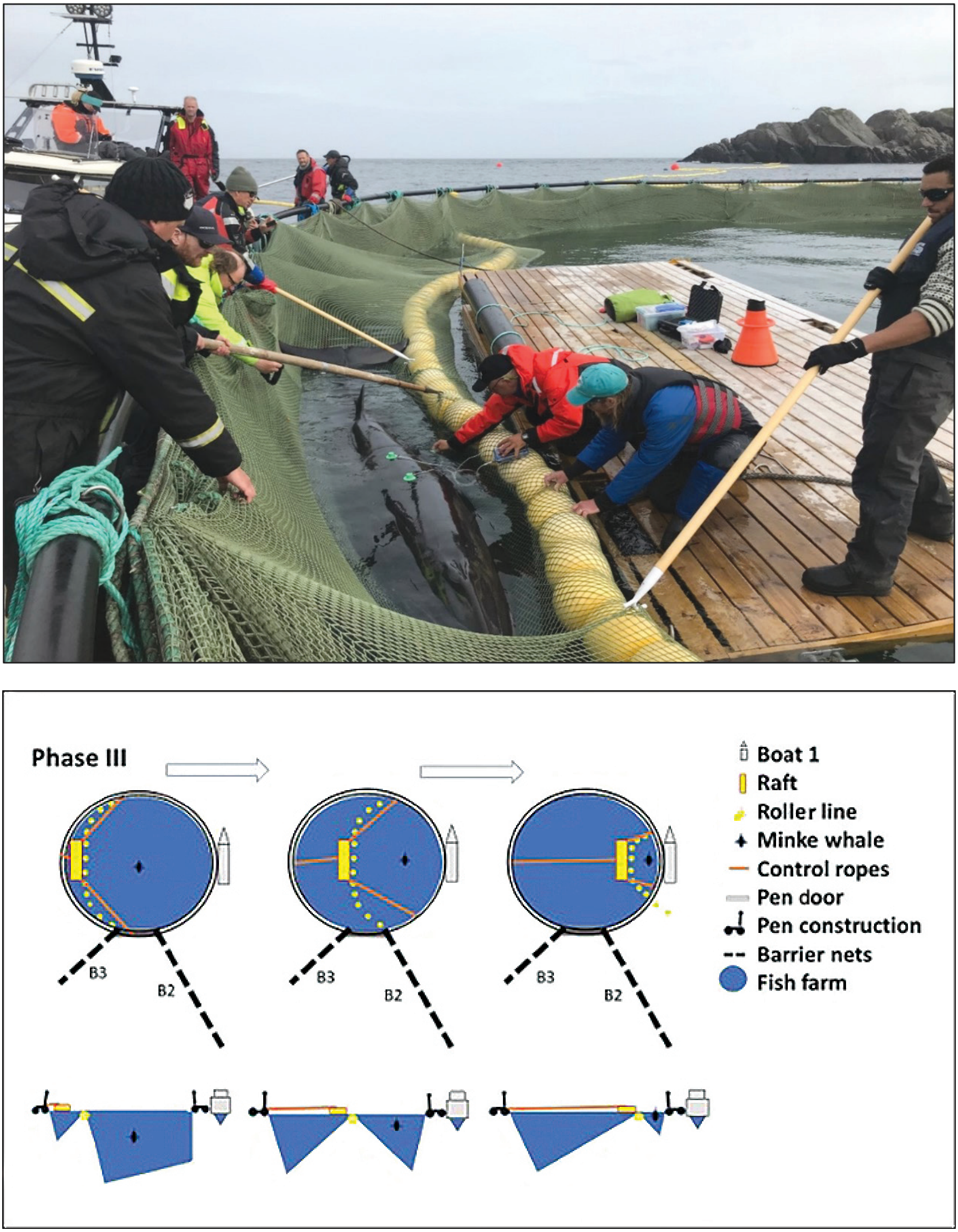

Figure 3. Phase III – getting the minke whale into the net hammock. *Upper panel:* Photograph of a minke whale in the net hammock. Crew on the raft access the whale for health monitoring (e.g., ECG electrode attachment, blood draws, etc.) or to perform other investigations (e.g., AEP hearing measurements, tagging). Crew on both sides help to keep the whale stabilized in the hammock. If necessary, the whale can be quickly released back into the aquaculture pen by pulling out the floating roller line and dropping the net (*Photo credit:* Rune Roland). *Lower panel:* The water volume around the minke whale is progressively reduced using a floating roller line (view from above in top row, profile in bottom row; progression occurs from left to right).

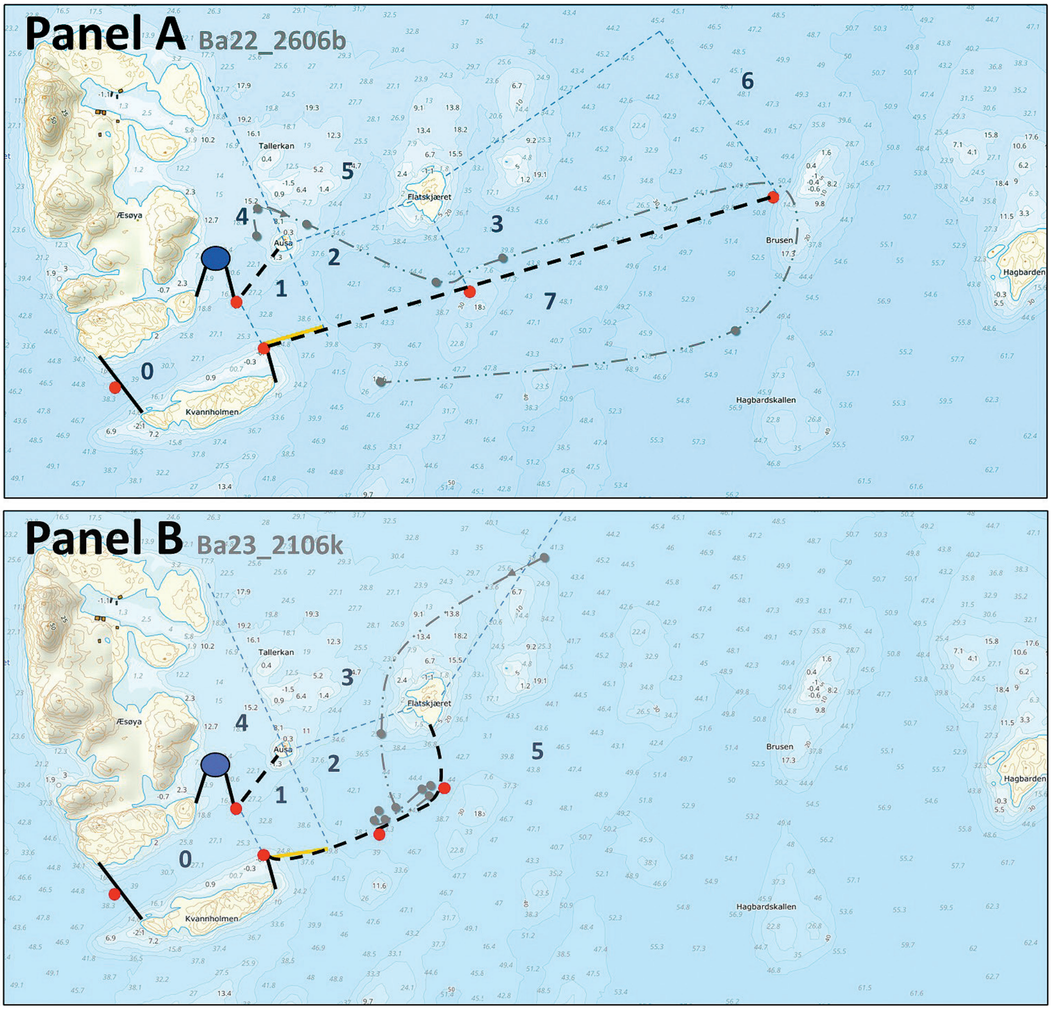

Figure 4. Example tracks of minke whales (light grey) approaching the CARS with the 2021/2022 net configuration (Panel A) and with the 2023 net configuration (Panel B). The CARS was divided into zones (0 to 7), primarily to enable rapid communication of whale sightings. The examples show the whales typically entering the CARS from the north (see Table 1). With the 2021/2022 net configuration, many whales escaped the CARS eastwards along the D-nets (Panel A). When the net configuration was changed in 2023, catch rates increased from one to two whales per year in 2021/2022 to seven whales caught in the catch basin (Zone 0) in 2023. Colors explained in Figure 2.

and #3) eastwards towards the aquaculture pen (Figure 2). Progress with the E-net was conducted at a slow pace (< 0.5 kts). Once the ends of the E-net reached the nets supporting the aquaculture pen (nets B3 and B2), lines attached to the ends of the E-net were handed to team members on the aquaculture pen so that the E-net ends could be manually pulled towards the door opening of the pen's outer net. During this final stage of corralling, boat engines were turned off to reduce noise. When the water volume between the E-net and the pen door was similar to the volume of the pen itself, the E-net was secured, and the whale was left to find its way through the door into the aquaculture pen.

The minke whale had to swim under the floating ring to enter the aquaculture pen. As soon as the whale was observed inside the pen, the net section that closed the pen door in the outer net was quickly released from the top and pulled down manually with ropes. Upon closing the door, the inner net was immediately pulled up by the attachment lines so that the whale was safely contained in the aquaculture pen. This process was performed in a controlled manner, utilizing multiple people spread

Table 1. The percent of first sightings in the different zones of the CARS with the net configuration used in 2021 and 2022 (Figure 4A), and the percent of the minke whales (*Balaenoptera acutorostrata*) tracked through the CARS sighted in each zone. Most animals approached from the north (38%; first sighted in Zones 4 and 5), fewer approached from the east (19%; first sighted in Zones 3 and 6), and 26% approached from an unknown direction (first sighted inside CARS, Zones 1 and 2). Only 17% of the whales sighted passed outside of the CARS (first sighted in Zone 7). Based on these data from 2021/2022, the configuration of the lead nets was modified in 2023 (see Figures 2 & 4).

Zone	% 1st sighting in zone	% whales sighted in zone
0	0	12
1	12	27
2	14	37
3	15	39
4	17	18
5	21	31
6	4	10
7	17	37

around the aquaculture pen ring. This allowed the net to be pulled up evenly such that no net pockets were created in which the whale might get entangled. The whale's position in the pen, behavior, and respiration rate were continuously monitored. Once the whale was fully contained within the aquaculture pen, the team moved to Phase III.

Phase III: Restraining the Minke Whale for Research Procedures—In Phase III of the catch process, the minke whale was physically controlled in a net hammock for instrumentation, measurement of AEPs (or other physiological measurements), and health monitoring.

Observations and recordings of minke whale behavior and respiration rates were done by two people in 10-min intervals from Boat #1, which was docked in a fixed position along the outside of the aquaculture pen ring. After observing the minke whale in the pen for a minimum of 2 h and determining that behavior and respiration rates appeared normal, the volume of the aquaculture pen was gradually reduced by first lifting up the inner net to 7 m depth and then pulling a chain of cork floats (roller line) under and across the inner pen net (Figure 3). The roller line was slowly (within 20 min) and manually pulled across the pen by six people walking on the floating pen ring. As progress was made, the inner net rolled over the roller line and reduced the water volume around the captured minke whale (Figure 3). Simultaneously, team members on the raft helped pull the net over the roller. As the roller line approached the opposite side of the ring, a hammock was formed from the remaining net beneath the whale. The whale was finally positioned in the net hammock between the raft and the floating ring of the aquaculture pen. It was supported below its body, but still mostly submerged and able to breathe freely. The whale could then be instrumented for health monitoring (e.g., ECG, respiration rate, blood draws) and for AEP measurements (Figure 3). Before release, the minke whales were instrumented with a fin-mounted satellite tag (Splash10-397A single pin design with a corrodible iron nut; Wildlife Computers, Redmond, WA, USA) to monitor post-procedural behavior (i.e., migration and dive behavior).

Post-procedure release of the minke whale was done by first pulling out the roller line and lowering the inner net to increase the water volume available to the whale. In this manner, the whale could be released back into the aquaculture pen's full volume within minutes. Observations were recorded for a minimum of 2 h after release back into the aquaculture pen, after which the inner net was dropped to the seafloor and the door in the outer net opened for the whale to re-enter the catch basin and return to the wild (Table 2).

Permits

Permits for this effort were acquired from the Norwegian Coastal Agency (Permit No. 2021/6-11/20/40) to anchor nets at sea for 6 wks (2 wks to deploy and recover nets and 4 wks of data collection) and to divert the shipping route. All nets were clearly marked with floats, buoys, and lights at the surface, and navigation warnings were issued. Permits were also acquired from the Norwegian Fishery Directorate (Permit No. 22/672 and 23/2507) to catch and release the minke whales. Permits for animal experimentation were given by the Norwegian Animal Research Authority (Permit Nos. 19/84343 and 22/241930).

Table 2. Timeline and duration of the different phases of the procedure for the three minke whales captured for AEP measurements. Due to signs of distress, Ba22_1706g was released before AEP measurements and satellite tag attachment. For Ba23_2606a and Ba23_2706c, both AEP measurements and satellite tag attachments were completed successfully before release. However, tag endurance of 16 and 64 d, respectively, is shorter than expected based on experience with this type of tag attachment in other species (Balmer et al., 2014).

Event	Ba22_1706g	Ba23_2606a	Ba23_2706c
Captured in catch basin	1635 h on 17 June 2022	0031 h on 26 June 2023	1718 h on 27 June 2023
Corralling started	2019 h	0249 h	1st attempt at 2004 h paused at 2230 h; 2nd attempt at 1215 h next day
Enter aquaculture pen	2319 h	0411 h	1528 h
Restraining process started	1632 h next day	0721 h	1740 h
Restrained in hammock	1641 h	0741 h	1753 h
Released from hammock	1710 h	0924 h	1830 h
Released to ocean	2345 h	1404 h	2230 h
Duration in Phase II	6.7 h	3.7 h	22.2 h
Duration of corralling	3.0 h	1.4 h	2.4 + 3.2 h
Duration in Phase III	24.4 h	9.9 h	7.0 h
Duration of restraining process	9 min	20 min	13 min
Duration in hammock	29 min	103 min	37 min
AEP measurement	No AEP data collection attempted	AEP collected successfully	AEP collected successfully
Post-procedural behavior Splash tag monitoring	No tag deployed	64 d	16 d

Procedures and protocols were also approved by the Institutional Animal Care and Use Committee of the National Marine Mammal Foundation (#15-2019 and #17-2021) with subsequent concurrence by the U.S. Navy Bureau of Medicine and Surgery (NRD 1185). Since the catch and release of baleen whales for research purposes is not routine, the permitting process required establishment of a safety protocol for animal handling, an emergency response protocol (if critical situations occurred), and a sedation protocol in case sedation of the whale was deemed necessary by the onsite veterinarian (see Supplemental Material S1; the supplemental material for this article is available on the *Aquatic Mammals* website). The sedation protocol was established by a working group of leading marine mammal veterinarians and anesthesiologists.

Results

Phase I: Observation and Corralling of the Minke Whale into the Aquaculture Pen

A total of 150 minke whales were sighted and tracked through the CARS over three field seasons: 19 animals in June 2021, 42 in June 2022, and 89 in June 2023. The majority of these minke whales were adolescents estimated to be < 5 m in length. Most of the whales approached the CARS from the north, not from the east as expected (Table 1). Sixteen of the 150 minke whales sighted in Phase I (11%) entered the catch basin (Figure 1), of which ten were contained (Phase II)—that is, the whales entered the catch basin, and the CARS door was fully closed. The other six whales entered the catch basin during the installation phase before the barrier nets were completely in place or escaped back out through the door before it was fully closed. With the 2021/2022 net configuration (Figure 2), many whales escaped the CARS eastwards around the D-nets (Figure 4). When the net configuration was changed in 2023 to prevent this, catch rates increased from one to two whales per year in 2021/2022 to seven whales caught in the catch basin (Phase II) in 2023.

The observed swimming behavior ($n = 150$) in Phase I was predominantly CNS (97% of sightings) with the remaining observations reported as 2% FVS and 1% SPY. The average respiration rate in Phase I was 0.6 ± 0.2 breath·min^{-1} ($n = 61$; including only animals tracked continuously for > 5 min). The majority of the sighted minke whales were observed either close to or following the lead nets. They were often seen inspecting the nets, but rarely observed physically touching them. Our observations clearly demonstrate the ability of these whales to detect and maneuver around moored nets (black nylon netting), and that it was possible to passively guide these individuals along such passive net barriers.

Phase II: Observation and Corralling of the Minke Whale into the Aquaculture Pen

Of the ten minke whales contained in the catch basin, seven of them escaped the basin in Phase II, either through gaps between barrier nets, between the barrier nets and the islets, or between the barrier nets and the aquaculture pen. Three of the whales were successfully corralled through the catch basin and contained in the aquaculture pen (Phase III; Figure 5).

When the minke whales entered the catch basin and the door was closed behind them, they showed CNS within the catch basin with an average respiration rate of 0.9 ± 0.2 breath·min^{-1} (*n* = 10) in the period before corralling. During corralling of the whales, their swim behavior became slightly faster and more vigorous, and they exhibited a small increase in respiration rate (Figure 5), particularly near the end of the corralling stage when the volume between the aquaculture pen's opening and the corralling net was decreasing (Figure 5). Even though the outer aquaculture pen door opening was large (10 × 15 m), the whales hesitated to enter the pen enclosure, maybe due to the large aquaculture ring at the water surface under which they had to swim. Still, this effort demonstrated that minke whales can be actively corralled in a specific direction in a slow and controlled manner by towing a net between two boats (Figure 2).

Phase III: Restraining the Minke Whale for Research Procedures

As soon as the minke whales entered the fish pen in Phase III, they displayed a stereotyped, always counterclockwise yet calm swim behavior with a normal respiration rate similar to Phase II before corralling started (Figure 5). When the pen's

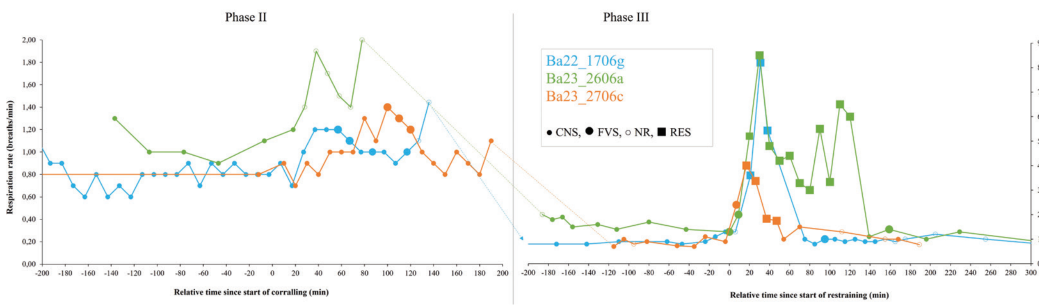

Figure 5. Respiration rate and swim behavior as a function of time in Phase II (left panel) and Phase III (right panel). The timeline is a relative time (min) since the start of corralling (time [T] = 0 min) for Phase II and start of reduction of the volume of the aquaculture pen (time [T] = 0 min) for Phase III. CNS = calm normal swimming, FVS = fast vigorous swimming, NR = behavioral data not recorded, and RES = the minke whale restrained in the net hammock. *Ba22_1706g* was caught at 1635 h (T = -224 min of Phase II) on 17 June 2022. Corralling began at 2019 h (T = 0 min in Phase II), and the minke whale entered the aquaculture pen at 2319 h (T = -1,033 min of Phase III). It was monitored in the pen for 26.8 h (due to bad weather passing). The process of getting the whale in the hammock was initiated at 1632 h the next day (T = 0 min of Phase III). The whale was restrained in the hammock at 1641 h (T = 9 min of Phase III). Due to signs of distress (arching and emesis), the whale was released back into the pen at 1710 h (T = 38 min of Phase III) before satellite tagging and AEP measurements could be completed. It was observed in the pen for 6.5 h before it was released back into the ocean at 2345 h (T = 433 min of Phase III). *Ba23_2606a* was caught at 0031 h (T = -138 min of Phase II) on 26 June 2023. Corralling started at 0249 h (T = 0 min of Phase II), and the minke whale entered the aquaculture pen at 0411 h (T = -200 min of Phase III). The restraining process started at 0721 h (T = 0 min of Phase III), and the whale was fully restrained in the hammock at 0741 h (T = 20 min of Phase III), released back into the pen at 0924 h (T = 123 min of Phase III), and back into the ocean at 1404 h (T = 403 min of Phase III). *Ba23_2706c* was caught at 1718 h (T = -1,147 min of Phase II) on 27 June 2023. Corralling started at 2004 h (T = -981 min of Phase II), but corralling failed in bad weather and was therefore paused at 2230 h (T = -835 min of Phase II). A second attempt was initiated the next day at 1215 h (T = 0 min of Phase II), and the minke whale entered the aquaculture pen at 1528 h (T = -132 min of Phase III). The restraining process started at 1740 h (T = 0 min of Phase III). The whale was fully restrained in the hammock at 1753 h (T = 13 min of Phase III), released back into the pen at 1830 h (T = 50 min of Phase III), and then back into the ocean at 2230 h (T = 290 min of Phase III).

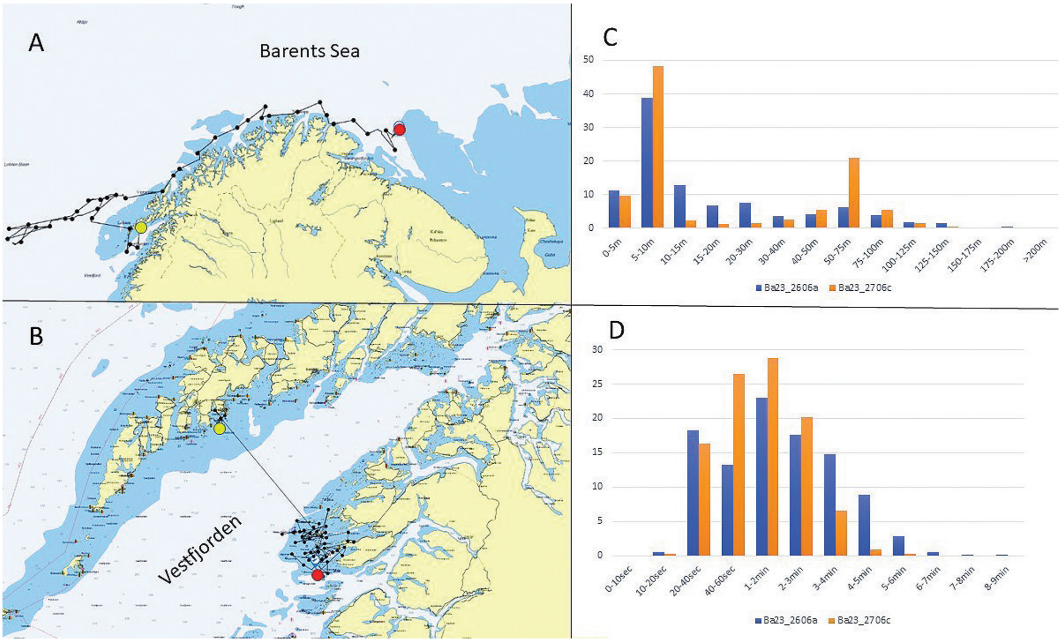

Figure 6. The first 2 wks of satellite tracks and dive behavior after release. Panel A and B are the tracks of Ba23_2606a and Ba23_2706c, respectively, with a yellow dot at the release position and a red dot at the position after 2 wks. Panel C shows percent dives in depth intervals, and Panel D shows percent dive duration intervals for both minke whales for the same period.

water volume was reduced (Figure 3), the whales typically displayed a more erratic, vigorous swimming behavior with increasing respiration rates (Figure 5). When they were restrained and touched the net in the hammock, all three minke whales responded with tonic immobility and tachypnea (Figure 5). Respiration became shallow and more frequent for a few minutes before it started to decrease again (Figure 5).

Three minke whales (Ba22_1706g: 3.8 m, unknown sex; Ba23_2606a: 4.4 m, female; and Ba23_2706c: 4.9 m, female) were successfully placed in the net hammock for testing (Figure 5). In accordance with the project's animal welfare protocol, the first collected minke whale, Ba22_1706g, was released from the hammock before AEP measurements and satellite tag attachment due to signs of distress—tachypnea (rapid breathing), arching, and emesis (vomiting). Lessons learned from this encounter led to modifications in the handling procedure to provide greater support and control at the axillary region and less constraint of the flukes that improved respiratory efficiency. For Ba23_2606a and Ba23_2706c, AEP measurements were successfully recorded (Houser et al., 2024), and satellite tags were attached to the dorsal fin (Figure 6).

Upon release back into the aquacultural pen, all three minke whales immediately returned to the stereotyped counterclockwise, calm swimming behavior with normal respiration rates recorded before handling (Figure 5). After release back into the wild, the whales resumed migration and active dive behavior (as recorded by satellite tags for 16 to 64 d), indicating that they did not exhibit any negative long-term effects from the procedure (Figure 6).

Discussion

A method for the live catch and release of minke whales for research purposes has proven feasible, allowing for continuous monitoring during handling, a quick emergency release, and a safe return to the wild. Three minke whales were caught and safely released, and initial measurements of the hearing of two of these whales were made (Houser et al., 2024). Based upon lessons learned over the 3 y, the method was steadily modified, resulting in progressive improvement in the catch procedure. For example, modifications were made to the lead net configuration to increase catch rates (Figure 4), and procedural modifications were made to improve animal welfare (see Supplemental Material S1).

Few attempts have been made to capture live mysticete whales for scientific purposes. Prior attempts were either unsuccessful or would be considered unacceptable under modern ethical standards (Vinje, 2022). Thus, the current project had few relevant studies on which to rely while developing our catch methodology. In the Danish pound net fishery, two minke whales were caught incidentally alive within the past 20 y. These trap nets are tended daily; however, the 15-y catch interval makes it unfeasible to be used as a method for planned scientific studies (J. Teilmann [co-author], pers. obs.). Furthermore, the most recent attempt to live-catch baleen whales in Iceland in 2007 (IOGP, 2022) failed because the purse seine net used could not be set quickly enough around the whales (J. Teilmann [co-author], pers. obs.). Learning from these prior approaches, our team determined to use moored stationary lead nets to guide minke whales into a large basin. Once contained in the basin, a whale could be slowly corralled into a smaller enclosure, similar to the Danish pound nets, where it could be lifted to the surface and held for testing.

Still, there were also challenges with the catch-and-release method described herein. For example, seven of the ten minke whales caught in the catch basin managed to find gaps between net junctions and escaped. Even though the nets were inspected regularly, the barrier nets were constantly pulled and pushed by ocean currents, tidal forces, and sea waves and, thus, dynamic gaps could occur. Minke whales orient themselves very precisely around nets (Kot et al., 2012; observations during this study), thereby enabling them to find those gaps and escape, if given sufficient time. Gaps at net junctions may be mitigated in the future by net placement correction following inspection of nets with an underwater drone and by greater net overlap.

Animal Welfare

The lead and barrier nets used in this study extended to the seafloor and were heavily weighted to eliminate the risk of animal entanglement. Free-hanging ropes and ropes crossing the capture basin were eliminated since fisheries interactions reported for mysticete whales are commonly associated with entanglement in free-hanging ropes (e.g., crab pot lines but not the nets themselves; Song et al., 2010). Other species like humpback whales (*Megaptera novaeangliae*), killer whales (*Orcinus orca*), harbour porpoises (*Phocoena phocoena*), and grey seals (*Halichoerus grypus*) were also sighted around the CARS, but as long as the nets were in the intended position, we observed no incidents involving marine mammal entanglement over the three field seasons conducted. However, in June 2023, prior to being fully operational, unusually strong (full moon) tidal currents and strong winds pulled the B1-net 80 m out of position such that one end ended up in deeper water where the lead-line no longer reached the seafloor. A minke whale became entangled in the free end of the net and died. This was discovered the next day following CARS repair and ROV inspection of possible damage to nets due to the storm. This whale was not under our care nor subject to our experimental protocol; nonetheless, the catch effort was immediately paused until all procedures were reviewed. After this incident, the anchor points of the nets were reinforced, and monitoring of the CARS increased in bad weather periods to prevent future incidents due to potential breakage of the CARS system.

Respiration rates are often used as a diagnostic indication of distress in wild animals (Breed et al., 2019). Øien et al. (2009) found the average respiration rates of 20 free-ranging minke whales to range from 0.5 to 1.2 breaths·min^{-1} with a population average of 0.8 breaths·min^{-1}. More detailed studies looking at respiration rate during different behaviors revealed that during normal swimming, the respiration rate ranges from 0.5 to 1.0 breaths·min^{-1}, and increases to 1.3 to 1.5 breaths·min^{-1} during rapid swimming (Folkow & Blix, 1993; Blix & Folkow, 1995; Kvadsheim et al., 2017). These observations are consistent with the respiration rates of the minke whales observed in this study. In confined spaces, surface rate can increase somewhat without being associated with increased metabolic demand or stress, thus we consider respiration rates between 0.5 to 1.5 breaths·min^{-1} within a 10-min period to be normal in the catch context presented herein. Respiration rates between 1.5 to 2.0 breaths·min^{-1} could indicate stress. Our minke whales exceeded normal respiration and calm swimming behavior for only a short time in the last phase of corralling (Figure 5), and what might be considered hyperventilation or tachypnea (> 5 breaths/min) was only observed briefly when the whales were fully restrained in the hammock (Figure 5). Thus, based on our observations of respiration rate and swim behavior, the last phase of the corralling and being restrained in the hammock seemed to be associated with increased stress, but any physiological stress due to handling likely subsided quickly after the stressor was removed. Our minke whales quickly returned to typical swim behavior and regular respiration rates following release into the aquaculture pen (Figure 5). Furthermore, the whale tracks and dive data from the satellite tags showed normal behavior following release back into the wild, with no indication of any lasting negative effect from the experiment (Figure 6).

Based on the three successful catches so far, it seems likely that this species responds to physical restraint by tonic immobility and tachypnea. Occasionally, arching and emesis were also observed. This implies a need for careful health monitoring of the minke whales while they are being held for testing, and release of any whales that show signs of distress (decompensation). To minimize distress, our procedures were modified along the course of the research. The last phase of the corralling and restraining process in the hammock was slowed down, and underwater noise was minimized (e.g., no machinery nor boat engines were used) to allow the whale to habituate to the increasingly smaller volume of water (Table 2). Intermittently, we also allowed the whale more space in the hammock so that it could freely flex without contacting the net. Finally, we decreased the handling time required for completion of research procedures (e.g., hearing tests, satellite tag attachment) by running these procedures concurrently.

Future Prospects

Maintaining mysticete whales in aquariums or laboratory facilities is unlikely due to their size, behavior, and feeding requirements. Thus, marine mammalogists would benefit from a field laboratory that is temporarily created in the ocean. Access to temporarily restrained mysticete whales would not only allow for studies of hearing (AEP measurements) but potentially other aspects of sensory physiology such as sight (Creutzfeldt & Kuhnt, 1973) or tactile senses (Markand, 2020). The potential importance of tactile senses was recently demonstrated in an anatomical study of the Antarctic minke whale (*Balaenoptera bonaerensis*), where it was proposed that the distributed rigid sensory hairs on the "chin" are used to detect prey at the interface of air and ice (Reichmuth et al., 2022). Other aspects of physiology could also be pursued such as respirometry (Wahrenbrock et al., 1974), cardiography (Smith & Wahrenbrock, 1974), ultrasonography (Curran & Asher, 1974), tissue (histology) and blood-related physiology (e.g., hematology, endocrinology, biochemistry panels, lipid analysis, stable isotopes, metabolomics, and molecular diagnostics of various diseases), morphometrics (Reidarson et al., 2001), and other aspects of animal bioacoustics (Winn et al., 1979). Tagging devices for use on cetaceans have advanced significantly since early tagging attempts by Evans (1974) and Watkins & Schevill (1977). Animal-borne tags are now available that can measure detailed aspects of the behavior and physiology of marine mammals (Andrews et al., 2019; Holton et al., 2021), including heart rate (Goldbogen et al., 2019), blood flow distribution (McKnight et al., 2019), cerebral processes during diving (McKnight et al., 2021), and, in the near future, possibly even auditory brainstem response from free-ranging animals (Smith et al., 2021). However, such modern tag technology may not be easily deployed remotely; thus, tag attachment will often require access to physically controlled animals, at least for a short period of time.

We acknowledge the complexity of this project, both in terms of field logistics and animal behavior. With our experience in all phases of the project, from handling nets to elimination of gaps at net junctions, corralling and restraining minke whales, and taking measurements of AEP, we will hopefully in the near-future provide the first empirical audiogram from a mysticete whale (Houser et al., 2024). This will enable us to better understand which sources of anthropogenic noise might impact them and how. In addition, data can potentially be used to guide mysticete auditory weighting functions (e.g., Southall et al., 2019) and validate anatomic hearing models of mysticete whales (e.g., Cranford & Krysl, 2015).

Note: The supplemental material for this article is available in the "Supplemental Material" section of the *Aquatic Mammals* website: https://www.aquaticmammalsjournal.org/index.php?option=com_content&view=article&id=10&Itemid=147.

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