Tools and Technology Article

Trial Implantation of Heart Rate Data Loggers in Pinnipeds

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ABSTRACT Pinnipeds are major consumers in marine ecosystems, and understanding their energy budgets is essential to determining their role in food webs, particularly where there is competition with fisheries. Food consumption and energy expenditure have been evaluated in pinnipeds using different methods, but the use of heart rate to estimate energy expenditure is potentially a very powerful tool suited to the life history of these animals. We tested a procedure for the subcutaneous implantation of heart rate data loggers to determine whether heart rate could be recorded for $\geq$1 year in free-ranging pinnipeds, as it has been in birds. We implanted 3 captive California sea lions (*Zalophus californianus*) and 3 captive northern elephant seals (*Mirounga angustirostris*) with heart rate data loggers and monitored their recovery and behavior in a controlled environment. In both species, the implantation site allowed for excellent detection of the electrocardiogram, and we observed heart rate signatures characteristic of behaviors such as resting and diving. Although all 3 sea lions recovered well from the implantation surgery, all 3 elephant seals showed a substantial inflammatory response for unknown reasons, and we removed the implanted data loggers. Subcutaneous implantation of data loggers is a powerful technique to study physiology, energetics, and behavior in California sea lions, but more work is required to realize the potential of this technique in northern elephant seals. (JOURNAL OF WILDLIFE MANAGEMENT 73(1):115–121; 2009)

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Pinnipeds are major consumers in marine ecosystems throughout the world, and the field metabolic rate (FMR) of these animals is a crucial input into models investigating interactions with fisheries and causes of population change (e.g., Winship et al. 2002). In the study of pinnipeds, most assessments of FMR have used the doubly labeled water (DLW) method (e.g., Costa and Gales 2003). However, this technique is not necessarily suited to the habits of these animals (Butler et al. 2004). An alternative approach to measuring FMR is the heart rate method, where heart rate (f_H) is measured in free-ranging animals and then converted to an estimate of the rate of oxygen consumption ($\dot{V}\,\mathrm{O}_2$) using a relationship calibrated under laboratory conditions (Butler 1993). The heart rate method has several advantages over the DLW method because it allows deployments of far longer duration and enables energy costs to be attributed to specific activities. To our knowledge, the heart rate method has only been applied in one species of free-ranging pinniped (Boyd et al. 1999), although free-ranging heart rate has been measured in several species (Hill et al. 1987, Thompson and Fedak 1993, Andrews et al. 1997, Hindell and Lea 1998), and calibration relationships have been developed in the laboratory in several more (Williams et al. 1991, Butler et al. 1992, Webb et al. 1998, McPhee et al. 2003). The difficulty of recording heart rate in pinniped species is probably the main reason why this technique has not been used more often. With one exception (Boyd et al. 1999), all studies of pinniped heart rate have used externally attached data loggers or transmitters. Attaching devices externally has several disadvantages. As devices are glued to the fur they are likely to be shed during molting periods, thus limiting the duration of deployment. Delicate devices and electrode wires can be damaged or removed by the study animal by scratching, biting, or abrasion on beaches or other surfaces. Perhaps most important, attaching devices to the outside of streamlined diving animals is known to increase their energy costs during foraging, as drag is increased, with a variety of negative consequences (Bannasch 1995).

Heart rate data loggers have been surgically implanted into the abdominal cavity of birds for >1 year with no effects on survival, breeding, or foraging (Guillemette et al. 2002, Green et al. 2004). Although heart rate transmitters have successfully been implanted into the abdominal cavity of small mammals (e.g., Lund and Folk 1976), no studies have successfully recorded the heart rate of larger animals in this manner. As an alternative to abdominal implantation in larger mammals, some investigators have implanted heart rate transmitters subcutaneously. This technique has proved to be satisfactory in some species (Holter et al. 1976, Giacometti et al. 2001, Arnold et al. 2006), but less successful in others (Ågren et al. 2000), suggesting that

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Table 1. Details of 6 pinnipeds equipped with subcutaneously implanted heart rate data loggers between December 2004 and October 2005 in California, USA.

No.	Species	Sex	Age	Mass (kg)	Date implanted	Date explanted
CS1[a]	California sea lion	F	Yearling	40.2	16 Dec 2004	20 Jan 2005
CS2	California sea lion	M	Juv (2–4 yr)	57.0	22 Mar 2005	2 May 2005
ES1	Northern elephant seal	F	Weaner (4–5 months)	37.5	6 Apr 2005	2 May 2005
ES2[a]	Northern elephant seal	F	Weaner (4–5 months)	53.2	26 May 2005	2 Jun 2005
ES3	Northern elephant seal	F	Weaner (4–5 months)	45.1	26 May 2005	2 Jun 2005
CS3	California sea lion	F	Ad (>5 yr)	76.2	14 Sep 2005	17 Oct 2005

[a] Because of technological problems with the data loggers, we obtained reliable data on heart rate and subcutaneous temperature from only these 2 animals.

responses may be specific to individual species or to the lifestyle of the study animals. Among pinnipeds, subcutaneous implantations of heart rate data loggers were successful in Antarctic fur seals (*Arctocephalus gazella*), but the limited memory size of the devices limited deployments to only 1–2 weeks (Boyd et al. 1999). However, Lander et al. (2005) showed that harbor seals (*Phoca vitulina*) can be successfully implanted with subcutaneous radiotransmitters for several months without affecting survival.

We conducted a trial of the subcutaneous implantation of heart rate data loggers in pinnipeds. We used captive individuals from 2 species, one each from the 2 major pinniped families: the eared seals, such as sea lions and fur seals (Otariidae), and true seals (Phocidae). Our study species were the Californian sea lion (*Zalophus californianus*), an otariid, and the northern elephant seal (*Mirounga angustirostris*), a phocid. Using captive animals allowed us to monitor welfare and physiological variables, such as heart rate and subcutaneous temperature, of subjects after surgery in a controlled environment. Our objectives were to determine whether each study species would accept implantation of a subcutaneously implanted device and whether a heart rate logger deployed subcutaneously could reliably detect the electrocardiogram (ECG) and allow recording of heart rate in pinnipeds.

STUDY AREA

We conducted all experiments at The Marine Mammal Center, Sausalito, California, USA. Animals were housed in a large outdoor pen with free access to a salt water pool 6 m in diameter and 1 m deep.

METHODS

We conducted all experiments during late 2004 and 2005 (Table 1). We used stranded animals at The Marine Mammal Center, rescued as part of their ongoing conservation and rehabilitation efforts, that had recovered from previous clinical disease but were underweight compared with wild animals of the same cohort (Greig et al. 2005). We used 3 California sea lions and 3 northern elephant seals in heart rate data logger trials. Individuals were a mixture of ages and sexes (Table 1). We fed sea lions and seals thawed herring twice daily. We performed our work under an Internal Animal Care and Use Protocol from the Marine Mammal Center (1/04) and under permit from the National Marine Fisheries Service (1065–1749).

We used custom-made data loggers designed and partly constructed by one of the authors (A. J. Woakes). These data loggers were the latest version of the device used previously in Antarctic fur seals (Boyd et al. 1999) and the same model as used in a variety of bird species, including ducks and penguins (Guillemette et al. 2002, Green et al. 2004). The device measured 37 mm × 27 mm × 14 mm and weighed 25 g. The body of the device was coated in wax and medical-grade silicone before implantation. Two electrode leads, 170 mm and 190 mm long, protruded from the body of the data logger and terminated in bullet ($n = 5$) or plate ($n = 1$) electrodes. We programmed data loggers to record heart rate (f_H) every 2 seconds and subcutaneous temperature (T_s) every 4 seconds. We measured temperature with a resolution of 0.01° C and calibrated it by immersing the coated data loggers in a water bath at a range of temperatures from 15–45° C. We sterilized all data loggers by gas sterilization, using ethylene oxide.

We fasted all animals for approximately 16 hours before anesthesia. We premedicated animals with 0.02 mg/kg atropine sulfate (Radix Laboratories Inc., Eau Claire, WI) given intramuscularly (IM) approximately 10 minutes before administration of anesthetic agents. We anesthetized sea lions using either 0.07 mg/kg of medetomidine (Domitor®, Pfizer Animal Health, Exton, PA) given IM or a combination of 0.04 mg/kg medetomidine and 1.0 mg/kg of tiletamine–zolazepam (Telazol®, Fort Dodge Animal Health, Fort Dodge, IA), IM, followed by masking with isoflurane (Aerrane®, Fort Dodge Animal Health). We anesthetized elephant seals using 0.8 mg/kg of tiletamine–zolazepam intravenously. We intubated all of the animals and maintained anesthesia with isoflurane in 100% oxygen. We mechanically ventilated the animals for the duration of the procedure. We monitored physiological parameters, including heart and respiratory rates, core body temperature, peripheral blood oxygen saturation measured by pulse oximeter, and end-tidal carbon dioxide levels throughout the procedure.

We shaved 3 areas of approximately 10 cm × 10 cm along the right thoracic and lumbar flank. The distance between the centers of the outer 2 areas corresponded to the maximum distance between the 2 outstretched electrode leads of the logger. We took care to ensure that the distal end of the anterior lead would not interfere with motion of the right shoulder and associated musculature. We sterilized all 3 areas using a routine surgical preparation, and we draped the sites using skin towels and surgical drapes. We made a longitudinal incision approximately 4 cm in length in the center area, approximately 10–15 cm lateral to the dorsal midline. We used sharp–blunt dissection to incise the blubber and subcutaneous tissue to expose the superficial thoracic musculature and fascia. We inserted the body of the logger ventrally into the incision, under the blubber and into the subcutaneous space, such that the electrode leads protruded from the opening. We then made a transverse incision approximately 2–3 cm in length in the anterior surgical field and used sharp–blunt dissection to expose the subcutaneous space. We inserted laparoscopic forceps (5 mm diam, 40 cm length) into the incision and tunneled them normograde to the central incision to grasp the distal end of the anterior (short) lead and pull it back through retrograde to exit from the anterior incision. We anchored the lead to the underlying fascia using one 3–0 absorbable monofilament (PDS-II®, Ethicon Inc., Somerville, NJ) suture with a cruciate pattern. We similarly placed the posterior (long) lead subcutaneously and anchored it in the posterior incision. Using 3–0 PDS-II, we closed all 3 incisions in 4 layers, including the subcutaneous tissue, subdermal fat (blubber), subcuticular layer, and skin. We used a continuous pattern in all layers, except the skin, in which we used an interrupted cruciate pattern. We gave an intraoperative injection of 1 mg/kg of flunixin meglumine (Banamine®, Schering-Plough Animal Health Corporation, Summit, NJ) IM for analgesia. We took radiographs to show placement of the leads (Fig. 1). We reversed the animals given medetomidine with 0.1 mg/kg of atipamezole IM.

All animals recovered from all anesthetic procedures uneventfully. Postsurgical recovery was also uneventful. Animals recovered alone in a pen with no access to food or water overnight, then we placed them into a pen with a saltwater pool in the morning, and they showed normal behavior, including good appetite and swimming behavior the following morning. We made focal observations of behavior at intervals throughout the deployment in one of the sea lions (CS1; Table 1). We made 10 observations, of between 45 minutes and 117 minutes ($\bar{x} = 88$ min). During each observation session, we continuously noted the location (in or out of pool) and activity, as well as any incidental disturbances (e.g., noise, disturbance by humans or other animals).

For removal (explantation) of the data loggers, we anesthetized the animals in a manner similar to that described above. We removed the remaining skin sutures and repeated the radiographs to show that no substantial shift in lead placement had taken place. Further details on wound healing and data logger removal in each species are provided below (see Results). After explantation surgery, we immediately placed all animals back into their normal pens and offered food the following morning; after which, we noted normal behavior, including good appetite and swimming.

We recovered data from the loggers using custom-written software on a computer using a RISC-OS operating system (RISCOS Ltd, Cardiff, United Kingdom). We recovered reliable data on f_H and T_s from one animal of each species (Table 1). We visualized data using Chart software (ADI Instruments, Bella Vista, Australia) and analyzed it using custom-written programs within the SAS system (SAS Institute, Cary, NC). We calculated mean f_H every 5 minutes to match data from laboratory calibrations between f_H and rate of oxygen consumption ($\dot{V}\,O_2$) in each species (Butler et al. 1992, Webb et al. 1998). We compared physiological variables with a simple correlation analysis.

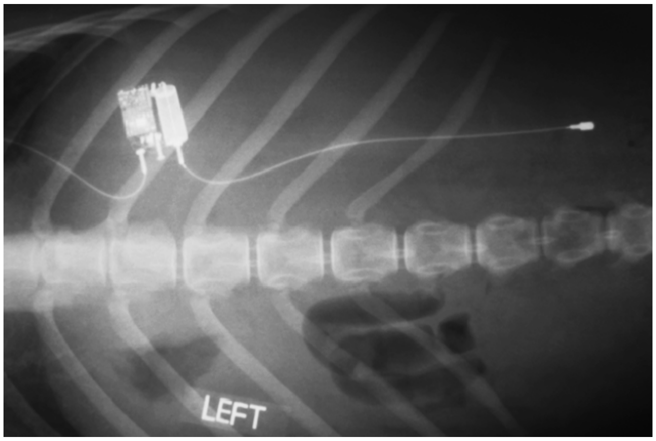

Figure 1. Radiograph of subcutaneous implantation on 16 December 2004 of heart rate data logger in a captive California sea lion in California, USA.

RESULTS

Northern Elephant Seals

All incision sites in the 3 elephant seals showed swelling and mucopurulent exudate of pus and mucus 3–5 days after implantation. In the first elephant seal, we flushed the wounds using chlorhexidine in an attempt to prevent rejection. However, the wounds continued to show dehiscence and split along the line of incision, and we removed the implant 26 days after implantation, when it was clear that it would be rejected. Because of the wound breakdown, it was possible to expose and elevate the logger and easily pull it through the central surgical site. We thoroughly flushed the pocket in which we had placed the logger with sterile saline, allowed the wound to drain, and left the incision to heal by second intention. We explanted the remaining 2 elephant seals 7 days after implantation because of wound breakdown and the experience with the first elephant seal described above. A marked inflammatory reaction was apparent in all 3 animals. Upon explantation, mucopurulent exudates were evident in all wounds and tracking along the leads. The body of the logger was wrapped in fibrinous material and necrotic debris. Histologic examination of biopsies of skin at the edge of the surgical site from the elephant seals showed inflammation and colonization with bacteria, and cultures produced a mixed growth of gram-positive and gram-negative bacteria. However, the wounds healed well in all the animals within 2 weeks of removal of the implant.

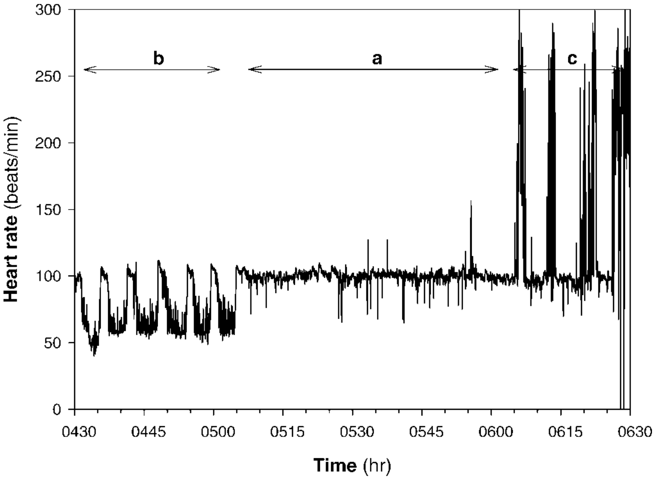

Figure 2. Example of a heart rate trace recorded for 2 hours from a captive northern elephant seal in California, USA. We sampled data on 28 May 2005, approximately 36 hours after implantation with a heart rate data logger. The 3 characteristic patterns we found in the heart rate trace are indicated: a) steady heart rate, b) episodes of bradycardia, c) high and variable heart rate.

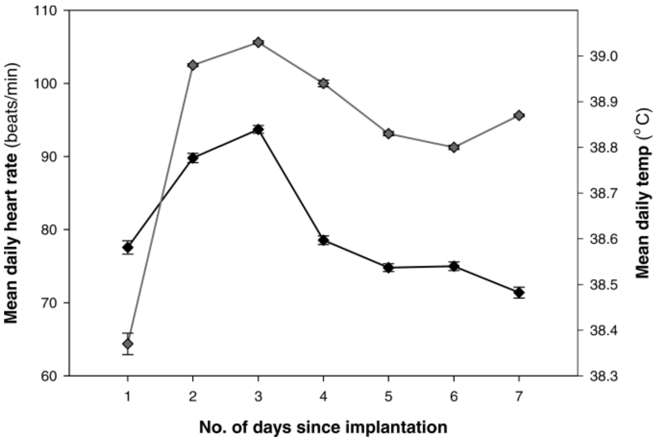

Figure 4. Mean (±SE) daily heart rate (black symbols) and subcutaneous temperature (gray symbols) of a northern elephant seal during 7 days (26 May 2005 to 1 Jun 2005) while implanted with a heart rate data logger in California, USA.

We obtained data from one of the animals with a 7-day implantation period. We could determine 3 characteristic signals in the heart rate trace of the seal (Fig. 2): steady heart rates around 100 beats per minute, episodes of bradycardia, and high and variable or noisy heart rate. A frequency distribution of heart rates showed a bimodal distribution with peaks around 60 beats per minute and 100–105 beats per minute (Fig. 3). The higher modal peak was thus approximately 1.7 times greater than the lower peak. Approximately 0.6% of heart rates were either zero beats per minute or >160 beats per minute. We detected these high heart rates during noisy intervals (Fig. 2). Mean daily f_H and T_s varied during the deployment period (Fig. 4). Notably, both f_H and T_s were elevated on the second and third days after surgery. We examined the distribution of heart rates on a daily basis and revealed a higher frequency of heart rates in the upper peak of the bimodal distribution and a much lower frequency of heart rates at the lower peak on these 2 days, which indicates that the elevation was most likely due to a decrease in the number of episodes of bradycardia on these days.

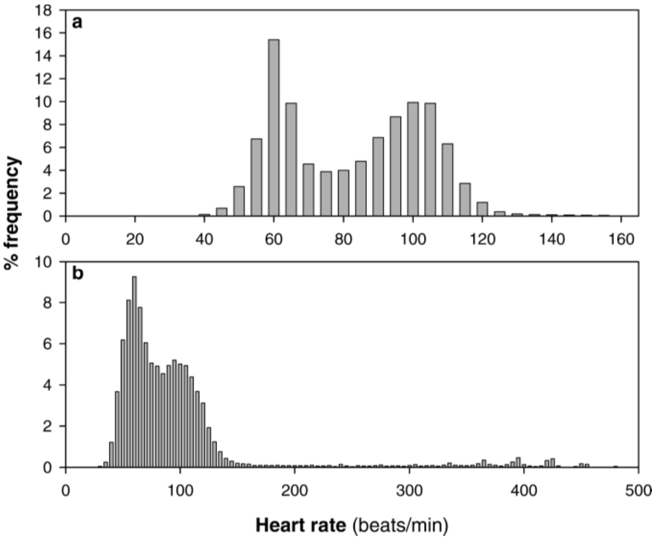

Figure 3. Frequency distribution of heart rates recorded every 2 seconds for a) approximately 7 days (26 May 2005 to 1 Jun 2005) in a captive northern elephant seal, and b) approximately 34 days (16 Dec 2004 to 20 Jan 2005) in a captive California sea lion in California, USA.

California Sea Lions

All incision sites in California sea lions healed well with minimal swelling and no exudate. To recover the loggers, we made one longitudinal incision of approximately 4–5 cm in close approximation to the old incision site over the body of the logger to reveal a healing granulation bed, and we removed the device through this incision. We obtained data from one animal for 35 days, which was the same animal (CS1) for which we made focal observations (Fig. 5). Again,

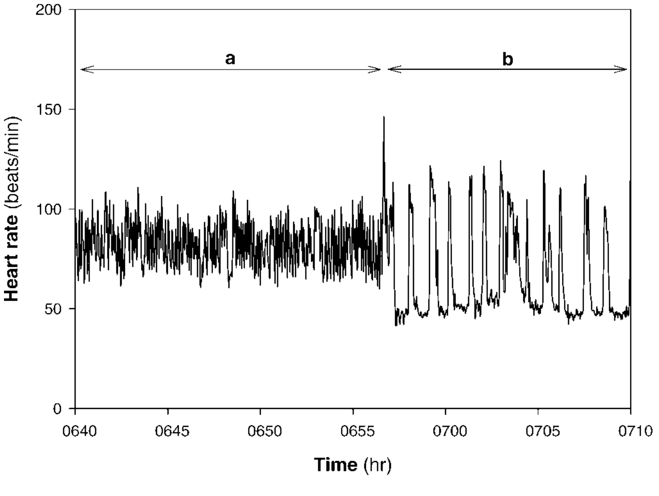

Figure 5. Example heart rate trace recorded for 30 minutes from a California sea lion in California, USA. We sampled data on 29 December 2004, approximately 13 days after implantation with a heart rate data logger. Two of the 3 characteristic patterns found in the heart rate trace are indicated: a) consistent heart rate, possibly indicating respiratory sinus arrhythmia, and b) episodes of bradycardia.

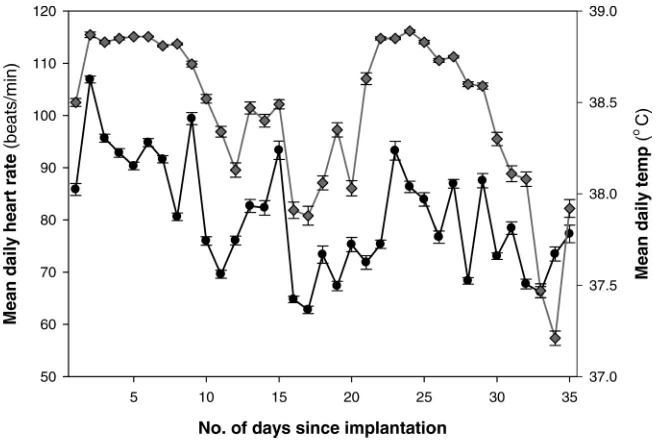

Figure 6. Mean (±SE) daily heart rate (black symbols) and subcutaneous temperature (gray symbols) of a California sea lion during 35 days (16 Dec 2004 to 19 Jan 2005) while implanted with a heart rate data logger in California, USA.

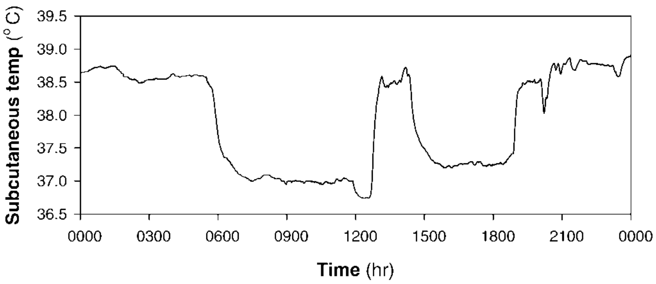

Figure 7. Variability in subcutaneous temperature for 24 hours in a captive California sea lion. We sampled data on 5 January 2005 in California, USA, approximately 20 days after implantation with a heart rate data logger.

we could detect 3 characteristic signals in the heart rate trace: consistent heart rates around 50–100 beats per minute, episodes of bradycardia, and high noisy heart rate (not shown in Fig. 5). During consistent heart rate periods, f_H oscillated with a period of approximately 50 beats per minute and a frequency of approximately 3.3 per minute. A frequency distribution of all heart rates again showed a bimodal distribution with peaks around 60 beats per minute and 95–100 beats per minute (Fig. 3). There was some variability in both f_H and T_s during the 35 days of the deployment (Fig. 6). Heart rate was variable between days of the deployment period but appeared to be relatively high during the first 7–8 days, before decreasing slightly. Subcutaneous temperature was also high during the first week of the deployment before decreasing, but T_s returned to these higher temperatures later in the deployment. There was a correlation between mean daily f_H and T_s ($P < 0.001$, $r = 0.68$). Changes in both f_H and T_s are likely to be related to diving activity. Further scrutiny of the heart rate trace and daily f_H distribution revealed relatively few episodes of bradycardia at the start of the deployment, when mean daily f_H was relatively high. We also observed rapid and abrupt changes in subcutaneous temperature, which were associated with diving activity (Fig. 7).

DISCUSSION

Effects of Subcutaneous Implantations in Northern Elephant Seals and California Sea Lions

The 2 species of pinniped showed different inflammatory responses to the subcutaneous implantation of the data loggers. We removed the devices from all 3 elephant seals before the devices were rejected. The elephant seal from which we obtained data showed fewer episodes of bradycardia on the second and third days after deployment (Fig. 4), which could represent natural variation in behavior or an inhibition of the behavior of the seal. Free-ranging macaroni penguins (*Eudyptes chrysolophus*) took an average of 52 ± 4 hours to return to their normal foraging routine after abdominal implantation with similar devices (Green et al. 2002). There was no indication of fever or increased heart rate or activity during the duration of the deployment, and the sea lion from which we obtained data also showed similar variability in behavior between days (Fig. 6). Because all elephant seal implantations were accomplished using the same sterile surgical procedure, type of implants, surgeons, and facility as those performed in the sea lions, it is most likely that the rejection of these implants is a function of species differences between elephant seals and California sea lions. Successful subcutaneous implantation of radiotransmitters in harbor seals (Lander et al. 2005) suggests that problems experienced by the northern elephant seals will not necessarily extend to all members of the family Phocidae.

A survey of the literature on implantation of recording and telemetry devices in other mammal species reveals similar variability in responses, both within and between species, with the lifestyle and habits of the subject being important factors (e.g., Davis et al. 1984, Guynn et al. 1987, Ågren et al. 2000). Subcutaneous implantation is the most straightforward procedure and is appropriate where the device will not be removed either through abrasion or scratching at the skin. All 3 California sea lions readily accepted their implanted device, and we recommend this technique for use in this species. The thick pelage and blubber layer of these animals is likely to protect the device from the abrasion experienced by other species. In northern elephant seals, further work is needed to test other coating materials or implantation sites.

Reliability of Subcutaneous Implantation for Detection of Heart Rate in Pinnipeds

The maximum heart rates recorded from northern elephant seals during either field (Andrews et al. 1997) or laboratory (Webb et al. 1998) recordings was 133 beats per minute. Similarly, mean maximum f_H recorded in 6 California sea lions exercising in a water flume was 155 ± 5 beats per minute (Butler et al. 1992). We assumed that the 5-minute periods during which we observed $f_H > 160$ beats per minute (0.6% of all recordings) in the elephant seal and >175 beats per minute (6.2% of all recordings) in the sea lion represented erroneous or spurious recordings by the data logger. In both species, we detected these high heart rates during noisy intervals of highly variable heart rate recording (e.g., Fig. 2). The data loggers are sensitive to any stimulation or movement of the electrodes so these spurious recordings could have been caused by the seals scratching, bumping, or lying on top of the data logger. Alternatively, high-intensity movement could have generated electrical activity in the musculature that led to erroneous recordings by the data logger. Our behavioral observations of the sea lion suggest that interference or vibration generated by loud machinery may be detected by the data logger and interfere with the normal processing of the ECG signal from the heart when the animal is ashore. Water may serve to isolate the data logger from this interference. Further bench tests of the device would be required to verify this, but it seems unlikely that this would pose substantial problems to free-ranging animals away from human habitation.

The bimodal distribution of heart rates observed in both species is typical of pinnipeds and diving animals in general. In particular, phocids, such as elephant seals, have a profound and sudden bradycardia associated with both diving and apnea–eupnea cycles while on land (Andrews et al. 1997). In free-ranging northern elephant seals, eupneic f_H was 1.4–1.5 times greater than apneic f_H while seals were on land and 2.6–2.8 times greater while seals were at sea. We observed a 1.7 times difference in the elephant seal, suggesting either that most episodes of bradycardia were on land or that they occurred in the pool but with apneic f_H elevated compared with free-ranging seals. The elephant seal in our study may have had an elevated apneic f_H because it was a weanling (4–5 months old), a period during which the physiological specializations associated with diving capacity, such as profound bradycardia, are developing rapidly (Zeno et al. 2008).

The 2 peaks in the bimodal distribution of heart rates in the sea lion were less pronounced and distinct from each other compared with those from the elephant seal, which is to be expected in an otariid seal because these animals have previously shown greater variation in bradycardia during diving (Boyd et al. 1999). In Antarctic fur seals, as in other diving species, maximum f_H during the predive tachycardia appears to increase with dive duration, whereas minimum f_H during the diving bradycardia tends to decrease with dive duration. This combination of factors will tend to broaden the width of both the upper and lower peaks in the distribution of heart rates. When comparing harbor seals and California sea lions, Williams et al. (1991) also noted that, during swimming, the bimodal pattern of heart rate was more pronounced in the phocid seal than in the otariid. Mean f_H of captive California sea lions at rest in a water channel was 72 ± 3 beats per minute (Butler et al. 1992). Approximately 45% of the heart rates we recorded were $<$72 beats per minute, suggesting that our sea lions spent a large amount of time either in bradycardia or ashore, where metabolic rate, and therefore f_H, tends to be lower in aquatic animals (Butler 2000).

Other studies have attempted to identify breathing rhythms in free-ranging animals by detecting a putative respiratory sinus arrhythmia (RSA) in heart rate traces (Andrews et al. 2000, Halsey et al. 2008). Preliminary examination of the heart rate trace in our study suggests that this may also be possible for California sea lions, because during periods where we observed the sea lion to be resting quietly out of the pool, we recorded frequent oscillations in heart rate. We observed decreases in T_s (Fig. 7), similar to changes in deep-body temperature during diving that have been recorded previously in seals (Hill et al. 1987). A study of Antarctic fur seals revealed regional heterothermy during diving, with a fluctuating difference between skin temperature and water temperature (Boyd 2000). Boyd (2000) hypothesized that the skin is an important thermoregulatory organ for otariids, and our preliminary results appear to confirm this.

MANAGEMENT IMPLICATIONS

We saw great variability between the 2 species we examined in their reaction to the subcutaneous implantation of a data logger, which illustrates the importance of testing implantation methods on each new species to be studied. Provided this precaution is followed, a subcutaneous location of a heart rate logger is suitable for measurement of heart rate in pinnipeds. Heart rate transmitters could also be located subcutaneously, provided that suitable receiving or relaying equipment could be located close enough to the study animal to receive the transmitted signal. The site we selected is convenient for the primary aim of estimating free-ranging energy expenditure from heart rate, but the subcutaneous location also provides opportunities to determine ventilation from RSA and regional heterogeneity and the regulation of blood flow and heat loss during diving.

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