Instrumentation for the remote monitoring of physiological and behavioral variables

R. D. ANDREWS
Department of Zoology, University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z4

Andrews, R. D. Instrumentation for the remote monitoring of physiological and behavioral variables, J. Appl. Physiol. 85(5): 1974–1981, 1998.—Few commercial products are available for investigators who wish to monitor multiple physiological and behavioral variables in unrestrained subjects. When telemetry is not practical, e.g., in studies of at-sea diving physiology, one of the only options is to design and build a custom data-logging instrument. This paper describes how a data logger was developed for the successful long-term monitoring of dive depth, swim speed, heart rate, water temperature, and multiple body temperatures from free-ranging northern elephant seals. The task was facilitated by using a commercially available single-board computer designed specifically for portable multichannel data acquisition and, where possible, off-the-shelf sensors/transducers available with integrated signal-conditioning circuits. A smaller data logger for monitoring the electrocardiogram, body temperature, and dive behavior of double-crested cormorants is also described to illustrate the flexibility and simplicity of this approach. Although it is customized for diving animals, with incorporation of the appropriate sensors the basic design should be applicable to studies of comparative, environmental, or exercise physiology involving most medium-to-large animals, including humans.

data logger; data acquisition; ambulatory monitoring; telemetry; diving physiology

TO STUDY PHYSIOLOGICAL systems it is often important to monitor the subject remotely to understand how a system operates in unanesthetized, unrestrained subjects. This is especially true if investigating the interactions between behavior and physiology, when it is essential to record the pertinent variables from subjects that are behaving as normally as possible (11). Toward these ends, numerous remote monitoring systems have been developed that enable the recording of many different physiological and behavioral variables. The majority of these systems involve the use of radio telemetry, a method that usually results in the smallest, lightest instruments possible for attachment to the research subject. However, telemetry is not always appropriate, especially when transmission range will be limited by the movement of the study subject through dense forest, urban settings, the inside of buildings, or an ocean. In such situations involving humans, captive animals, or free-ranging animals that can be easily recaptured, a device that is carried by the subject and logs data for later retrieval is an alternative to radio telemetry.

The study of diving physiology is one area of research where biotelemetry is sometimes not applicable. One of the earliest data-logging instruments (7) used on a diving animal was constructed from a bourdon tube, a kitchen egg timer, and a smoked glass disk to record the diving depth of Weddell seals (Leptonychotes weddelli). Other types of archival instruments that have been used on diving animals include those that trace the depth of dives over time onto photographic film using LEDs (8) and Holter monitors modified to record the electrocardiogram (ECG) of northern elephant seals (Mirounga angustirostris) on magnetic tape (1). Most such devices have limited usefulness because of their large size and inability to simultaneously record many different physiological and behavioral variables. The best technique for producing a small, multivariable recorder is the use of microcomputers to control the logging of data into solid-state memory, a method pioneered for use in diving animals by Hill (6) and recently adopted by other research groups (10, 12).

Although the value of such data loggers is tremendous, their general availability is limited. When research projects required data loggers that were not available from colleagues or commercial vendors, previous investigators have had to design and produce an appropriate instrument. This method requires one to identify a suitable microprocessor and interface it with the necessary electronics, e.g., a clock crystal, voltage regulator, analog-to-digital converter, and memory chip, a process that requires substantial training in electronics or considerable assistance from an electrical engineer. I initially adopted this approach but found it to be difficult and expensive. A new system was needed that could be easily adapted to record different types of physiological and behavioral variables and could be reprogrammed quickly by an end user with minimal experience in computer programming. The instrumentation presented here meets these needs and satisfies the basic requirements I defined for a suitable data-logging system (Table 1). Two different devices are
presented here to illustrate some of the diversity in instrument design and application possible with this system. Both devices are based on an inexpensive, commercially available, single-board computer designed specifically for portable data acquisition that enables the end users or their local bioengineer to concentrate on the less difficult tasks of interfacing to the appropriate sensor electronics and packaging and applying the finished data logger to the research problem.

**COMPUTER BOARD**

To simplify the task of building a custom data logger, I chose to use an off-the-shelf computer (Tattletale Fast Lite, Onset Computer, Pocasset, MA) capable of handling the power management, timing, input-output control, analog-to-digital (A-D) conversion, and communication needs of a portable data-acquisition system. The Tattletale Fast Lite contains on a single board (7.8 × 5.4 cm) a Motorola 68HC05 microprocessor, a voltage regulator for a 5-V output, eight eight-bit analog, eight digital, and two count input channels, 512 kbytes of random access memory, a liquid crystal display (LCD), and a universal asynchronous receiver/transmitter. The Tattletale Fast Lite’s native 8-bit resolution can be extended to 13- or 15-bit resolution with a built-in dithering technique. Analog sampling is possible at rates as high as 25 kHz, and the current during acquisition is minimally 600 µA and falls to 200 µA when acquisition is completed. Although similar products exist, including smaller ones with lower power consumption, the Tattletale Fast Lite was chosen because of its ease of use. The Tattletale Fast Lite programming language, LiteL, is a tokenized version of BASIC, designed to facilitate common data-logging functions. LiteL can easily be mastered by those with a cursory knowledge of computer programming. An example program used in a northern elephant seal study is included in the appendix. The Tattletale Fast Lite includes proprietary software for writing, compiling, and uploading programs, as well as for creating instant graphs on downloading data. The resulting quick data visualization was quite useful in the design of sensors and in the initial stages of our experiments.

**SENSORS FOR STUDY OF NORTHERN ELEPHANT SEALS**

For this application, the following variables had to be monitored: dive depth, swim speed, heart rate, and ambient and body temperatures. Depth below the surface was sensed by a 0- to 10-MPa pressure transducer connected to a proprietary signal-conditioning circuit (model PA7-100, Keller PSI, Hampton, VA) to ensure thermal compensation and a linear 0- to 5-V output. The pressure transducer was calibrated with a compressed gas pressure gauge comparator and a National Institute of Standards and Technology-traceable precision gauge. After input into the Tattletale Fast Lite’s eight-bit A-D converter, the transducer provided a resolution of 3.4 m of seawater over the range 0–900 m. Swim speed was transduced using a magnetized turbine (Flash Electronics, Dachau, Germany). The alternating electrical field produced in the sensing coil mounted under the turbine was converted to one square-wave pulse for every rotation of the turbine, and the pulses were input into one of the Tattletale Fast Lite’s digital count channels. The output of the turbine was calibrated by mounting a completed data logger on the back of a Fiberglas full-scale model of a seal that was towed through a tank of water at known velocities from 0.1 to 3.0 m/s. After each deployment on an elephant seal, this calibration was checked and corrected by comparing speed with the derivative of the scaled depth signal (dP/dt) for every sampling interval (6). Although swim speed will usually exceed the rate of change in depth because of the horizontal component of the seal’s speed, when the seal swims directly vertically, swim speed should equal dP/dt. I assumed that throughout the speed range there were at least a few sampling intervals that consisted of completely vertical swimming. In a graph of dP/dt plotted as a function of speed, such points should fall along a line with a slope of 1. Therefore, if this maximum dP/dt-to-speed ratio did not equal 1 the appropriate correction factors were applied to the speed data.

Heart rate was measured by using a human pulse-transmitter system (Polar Electro, Port Washington, NY). This approach ensured that if the ECG leads became entangled and the electrodes fell off, the data logger would remain attached to the seal. The ECG signal was conducted through titanium surface electrodes (1) and neoprene-insulated wire to an R wave detector/transmitter [Polar transmitter printed circuit (PC) board]. The front-end amplification circuit on the detector/transmitter was modified to increase its gain and, therefore, make the detector more sensitive to the low-amplitude R waves found on a seal immersed in seawater. On each detection of an R wave the Polar unit transmitted ~36 cycles of 5-kHz sine waves. These transmissions were received by a circuit board (Polar OEM receiver PC board) that included a coil antenna and a circuit that converted the 5-kHz bursts into 10-ms, 3.0-V square-wave pulses that were fed into the Tattletale Fast Lite’s second count channel. Whether in seawater or air, the range of the transmitter was ~1 m when the transmitter’s coil antenna was approximately

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**Table 1. Specifications for a data logger system to record multiple physiological and behavioral variables from diving animals**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum size</td>
<td>15 × 8 × 4 cm</td>
</tr>
<tr>
<td>Minimum no. of analog inputs</td>
<td>6</td>
</tr>
<tr>
<td>Minimum no. of digital input/outputs</td>
<td>3</td>
</tr>
<tr>
<td>Minimum memory size</td>
<td>128 kbyte</td>
</tr>
<tr>
<td>Maximum average current drain</td>
<td>2 mA</td>
</tr>
<tr>
<td>Life expectancy of data logger</td>
<td>&gt;1 yr</td>
</tr>
<tr>
<td>Ambient temperature range</td>
<td>−2 to 40°C</td>
</tr>
<tr>
<td>Security</td>
<td>Seawater proof, pressure proof to 2,000 m, able to withstand drop to floor from 1 m</td>
</tr>
</tbody>
</table>

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parallel to the receiver’s coil antenna but otherwise was <0.3 m. Therefore, two receiver boards were electrically connected in parallel and physically placed at right angles to one another to ensure that the range of the transmitter was less dependent on the orientation of its antenna.

Ambient and body temperatures were sensed using epoxy-encapsulated thermistors (Fenwal Electronics, Milford, MA) connected to a signal-conditioning circuit with a nonlinear 0- to 5-V output. The thermistors were calibrated in a constant-temperature water bath over the range −1 to 40°C using a National Institute of Standards and Technology-traceable thermometer with 0.05°C gradations. After input into the Tattletale Fast Lite’s A-D converter the temperature circuits provided a resolution of 0.2°C, with an absolute accuracy of ±0.2°C. In experiments that did not involve heart rate monitoring, it was possible to measure stomach temperature using a stomach temperature telemeter (STT) built by modifying a Polar R wave detector/transmitter. An R wave simulator circuit consisting of a timer (model 555, National Semiconductor, Santa Clara, CA) and a thermistor/resistor-capacitor circuit produced a signal with a pulse rate that varied only with the temperature at the sensing thermistor. The output was connected to the ECG inputs on the detector/transmitter to produce a temperature-dependent telemeter with transmissions that were received and decoded as described above for heart rate. Over the temperature range of 30–39°C, the STT pulse rate varied from 650 to 1,000 pulses/min. Counting the number of pulses received in a 10-s period allowed for a resolution of 0.2°C at 30°C. The STT was calibrated by the same method described for the ambient and body temperature thermistors.

PACKAGING OF DATA LOGGER FOR STUDY OF NORTHERN ELEPHANT SEALS

The sensors described above were connected to a Tattletale Fast Lite (Fig. 1). Most of the sensor circuitry was assembled on a single PC board stacked 8 mm below the Tattletale Fast Lite computer board. A 15.5-mm hole was created in the rear of the swim-speed transducer housing to allow mounting of the pressure transducer and its circuit board. This assembly was filled with rigid epoxy resin (Sealtronics, Industrial Formulators, Burnaby, BC, Canada) and then mounted on top of the Tattletale Fast Lite. The data logger was powered by two 3.6-V lithium AA cells (LS14500, SAFT, Romainville, France) with a capacity of 1.9 Ah at 7.2 V, providing ~40 days of continuous operation. The entire data-logger assembly was cast in Sealtronics epoxy, resulting in a final mass of 260 g. Silicone rubber (RTV 118, GE, Waterford, NY) provided strain relief where the three body temperature thermistor leads exited the data logger. The three pins of the Tattletale Fast Lite’s universal asynchronous receiver/transmitter could be accessed for connection to a portable computer’s RS232 serial communications port by removing a thin layer of epoxy. The separate heart rate R wave detector/transmitter was also cast in epoxy after attachment of one lithium 1/2AA cell (SAFT LS14250) with a capacity of 0.8 Ah at 3.6 V, which provided ~250 days of constant operation.

Fig. 1. Top: expanded view of data logger. Bottom: simplified diagram of data-logger system as used on a juvenile northern elephant seal. Because heart rate transmitter and stomach temperature telemeter (STT) operate on same frequency, they cannot be used simultaneously. PC, printed circuit; LCD, liquid crystal display.
operation at an average heart rate of 60 beats/min. The STT circuit was powered by one SAFT LS14500 cell to provide ~100 days of continuous operation at 37°C. The STT assembly was cast in Sealtronics epoxy in a cylindrical shape (4 cm diameter × 7 cm long), with the thermistor located along the outside edge midway along its length.

APPLICATION TO NORTHERN ELEPHANT SEAL STUDY

Data loggers in the configuration described above and illustrated in Fig. 1 were used with juvenile northern elephant seals in the translocation method that was used for a study of heart rate during diving (1). Seals that were captured at the Ano Nuevo rookery were instrumented at the Long Marine Laboratory in Santa Cruz, CA. The data loggers and heart rate electrodes were attached as described previously (1). The amplified ECG and the detector circuit trigger output of the Polar R wave detector/transmitter were accessed and displayed on an oscilloscope during the instrumentation procedure to verify proper R wave detection. The three body temperature thermistor probes were inserted through one spot in the lumbar region of the seal’s dorsal surface and terminated subcutaneously, at the muscle-blubber interface, or in deep muscle. The next day each seal was transported to and released at a site on the opposite side of Monterey Bay. The data-collection protocol consisted of variable-length sampling intervals (see APPENDIX for a sample control program). Between the sampling times the number of pulses from the swim-speed circuit and the telemetry receiver circuit were accumulated. At the end of each sampling interval, these counts were stored in memory, and the appropriate analog channels were sampled and their values were stored in memory. The values from the two digital count channels (swim speed and heart rate or STT pulse rate) were stored as 2 bytes each, and the values from the five analog channels were stored as 1 byte each. When sampling heart rate, swim speed, and dive depth every 10 s and ambient temperature and the three body temperatures every 60 s, the Tattletale Fast Lite’s 512-kbyte memory lasted for 10.7 days. The data loggers were removed and downloaded to a notebook computer after each seal returned to the beach.

EVALUATION OF DATA-LOGGER PERFORMANCE IN NORTHERN ELEPHANT SEAL STUDY

Before the design described above was finalized, earlier versions of the elephant seal data logger suffered failures mostly related to encapsulation and security. For example, in some initial prototypes the circuit boards were first cast in flexible silicon gel, to facilitate future circuit modifications, before being cast with an outside layer of epoxy. Although an attempt was made to remove all the air bubbles under a vacuum, even the slightest bubble left the epoxy shell vulnerable to cracking at the enormous pressures often experienced by elephant seals. Solid casting in epoxy resulted in only one failure, which was apparently caused when a 200-kg seal rolled over onto some rocks so that the data logger was impacted by a sharp rock point. This data-logger design was used on 14 deployments lasting from 1 to 30 days. There were some electrode lead and body temperature lead failures, often at the thermistor solder joints. There were no failures caused by internal malfunctions. Overall the data loggers performed very well in this application, enabling the simultaneous monitoring of dive behavior, heart rate, and body temperature profiles from free-ranging elephant seals. An example data plot from one elephant seal is shown in Fig. 2. With these types of data collected simultaneously, hypotheses concerning the distribution of blood flow to peripheral areas such as the skin and to locomotory muscle during diving can be addressed.

This success led to the development of another data logger based on the Tattletale Fast Lite for a study of the diving physiology of captive, but voluntarily diving,
double-crested cormorants (Phalocrocorax auritus). This study also required the monitoring of dive behavior, heart rate, and body temperature, but different sensors and packaging were necessary. One goal of the cormorant study was to determine the ontogeny of the heart rate response to diving, and the initial submergences of fledgling cormorants can last as little as 1 s. To obtain the necessary time resolution and because the ECG of an exercising cormorant can be too noisy to rely on an R wave detector, it was necessary to record the ECG directly. Other data-logger modifications included much higher sampling rates and, because of the cormorants’ small size (2 kg), smaller packaging, changes that were easily accomplished with this system.

**SENSORS FOR STUDY OF DOUBLE-CRESTED CORMORANTS**

Unlike the free-ranging elephant seals, the captive cormorants were expected to spend much of their dive time at very shallow depths, often swimming submerged at depths of only 0.2 m. Therefore, instead of monitoring dive depth, we simply wanted to record with certainty whether a bird was at the surface or submerged. Submergence was sensed by a small liquid-level sensor (model LL105100, Microswitch, Freeport, IL). This optical sensor has an integral LED and optoschmitt circuit. When above water, the LED is internally reflected to an optoschmitt circuit and a high output value is produced, but when submerged the change in refractance at the boundary layer allows light to escape so that the output is zero. The response time of this sensor is ~0.5 s in water. The ECG electrodes were prepared by stripping the insulation from a 5-cm section of Teflon-insulated multistrand stainless steel wire and coiling this section into a 0.5-cm-diameter loop. The ECG was conducted through two such electrodes to a Polar heart rate detector/transmitter board with no antenna coil. The Polar board was used as an ECG amplifier because of its small size, low power consumption, and circuit characteristics that produce an ECG with a very stable baseline and little noise. The Polar's R wave detector circuit was bypassed, and the amplified ECG signal was fed into one of the Tattletale Fast Lite's A-D channels. Body temperature was sensed with a single thermistor (as described above for the elephant seal sensors). The Tattletale Fast Lite's 13-bit dithering routine allowed a resolution of 0.02°C, although the absolute accuracy remained at ±0.2°C.

**PACKAGING FOR STUDY OF DOUBLE-CRESTED CORMORANTS**

The sensors described above were connected to a Tattletale Fast Lite (Fig. 3). The Tattletale Fast Lite's LCD screen and LCD control chip were removed to reduce size, and a single LED was used to signal the operation of the data logger. A reed switch connected across two of the Tattletale Fast Lite's input-output lines was installed so that a magnet could be used to
manually trigger the onset of data acquisition. The body temperature circuit was assembled on a small PC board that was mounted directly on the Tattletale Fast Lite computer board, as were the ECG amplifier board and the submergence sensor. The data logger was powered by two 3.6-V lithium coin cells (TL-5186, Tadiran, Port Washington, NY) that were mounted slightly above the computer board on a thin layer of paraffin wax to facilitate future battery replacement. The entire data-logger assembly was cast in Sealtronics epoxy, and silicone rubber provided strain relief where the ECG and body temperature lead assembly exited the data logger. The 7.0-cm lead assembly terminated in a miniature four-pin waterproof plug to allow connection to the implanted leads. The mass of this data logger was 75 g.

APPLICATION TO DOUBLE-CRESTED CORMORANT STUDY

As illustrated in Fig. 3, a data logger in the configuration described above was used on double-crested cormorants. The two insulated ECG electrode leads and the two insulated leads for the single body temperature thermistor were encased in a length of silicone rubber tubing filled with latex rubber to further protect them from bodily fluids. The thermistor tip was placed 0.2 cm proximal to the sensor end of this lead assembly, and both ECG electrode leads extended past the silicone rubber tubing so that one uninsulated ECG electrode was 0.5 cm distal to the tubing end and the other electrode was 4.5 cm from the tubing end. For lead implantation, a 500-ml mask was placed over the bird’s head, and anesthesia was induced with 1.5–2.5% halothane in oxygen. The bird was then intubated and artificially ventilated (tidal volume = 50 ml, respiratory frequency = 17 min⁻¹), and anesthesia was maintained with 0.75–1.5% halothane. The lead assembly was placed so that one electrode and the thermistor lay near the apex of the heart and the other electrode lay near the base, a separation of ~4 cm. The lead assembly was led out of the peritoneum and tunneled subcutaneously to the exit site on the midline of the dorsal surface ~4 cm cranial to the caudal end of the synsacrum. The data-logger end of the lead assembly terminated in a miniature four-pin waterproof connector that was fixed in place by gluing it to a small neoprene patch that was mounted on the bird’s feathers with cyanoacrylate adhesive.

Before a trial the data logger was attached to a harness that was then placed on a cormorant’s back, and the data logger’s ECG-electrode/thermistor leads were connected to the implanted leads. In one of the experimental settings, chopped herring was placed at the bottom of a 13-m-deep tank, and the cormorants were released into the tank. The cormorants usually began diving for the fish immediately and typically made 5–15 dives over the course of 3–10 min. The data-acquisition protocol consisted of sampling the ECG at 100 Hz, the submergence sensor at 2 Hz, and the body temperature thermistor once every 30 s. At this rate the data logger’s memory was filled in 85 min. At the end of a trial the data logger was removed and downloaded to a notebook computer. Heart rate was derived from the ECG by identifying QRS peaks by eye.

EVALUATION OF DATA-LOGGER PERFORMANCE IN DOUBLE-CRESTED CORMORANT STUDY

The data logger was used on 15 cormorants to obtain >700 h of recording without instrument failure (D. Enstipp, R. D. Andrews, and D. R. Jones, unpublished observations). Data from one dive bout are shown in Fig. 4, which illustrates the sometimes profound bradycardia observed, as well as the tendency for body temperature to decline over the course of a foraging bout. Other recent studies have suggested that some
seabirds may experience extreme regional hypothermia (3–5), especially when foraging in cold water. In light of these results, subsequent cormorant studies may utilize a data logger that includes the STT system described for elephant seals and additional body temperature thermistors. Modifications such as these could be made quickly and easily with this system.

Although the cormorant data logger is the smallest ambulatory ECG monitor that I know of, it is possible that its size may have affected diving performance or the physiological response to diving. The added drag of recording instruments has been shown to increase the cost of swimming in penguins, but this effect can be reduced by streamlining the device (2). However, the cormorant data logger has such a low profile and small frontal area (<5% of a cormorant’s frontal area) that streamlining would probably not have been very effective (9). The harness was likely the biggest contributor of added drag. It was used because the data logger had to be removed after each recording session to avoid the damage caused by the pecking of other cormorants in the aviary. When possible, the data logger should be glued or taped to the feathers. Nonetheless, no difference was observed in swimming behavior or dive times between instrumented and uninstrumented cormorants.

APPENDIX

A sample LiteLanguage program for controlling a Tattletale Lite data logger customized to record swim speed, heart rate, dive depth, water temperature, and three body temperatures. Section labels are denoted by all capitals; comments are preceded by a single quote. For conciseness, the conversion subroutines (e.g., “conv-speed”) are not shown.

```
START outputs 0,1,2,3,4,5,6,7 'set all I/O lines as outputs to save current drain
vlow 'set the data logger to run on low voltage mode (4.5 V)
DATA loop 6 'loop through the next subsection 6 times, which takes 60 sec
sleep 100 'wait for 100 "sleep" (0.1 sec) intervals (=10 sec) to count swim speed and heart rate pulses
plotpoint "Swim", v9, conv-speed 'run conversion subroutine entitled conv-speed on the number accumulated in count channel 1 (v9) and then save to memory the calibrated swim speed value in m/s
plotpoint "Heart", v10, conv-beat 'save to memory heart rate in beats/minute
dear v9 'zero the accumulator
store v9 'clear v9 (count channel 1) by placing the accumulator value of zero in v9
store v10 'clear v10 (count channel 2)
pinlow 0 'return I/O line 0 to low to turn off FET and power off the pressure transducer circuit
atod8 v0 'make an 8-bit A–D conversion of pressure at A–D channel 0 and store in variable v0
pinhigh 0 'return I/O line 0 to high to turn off FET and power off the pressure transducer circuit
plotbyte "Depth", v0, conv-press 'save to memory the calibrated depth in meters of seawater
endloop 'drop out of loop after 60 sec to sample water and body temperatures
pinlow 1 'Turn on FET to supply power to the temperature circuits
atod8 v1 'make 8-bit A–D conversion of subcutaneous temperature on A–D channel 1 and store in variable v1
atod8 v2 'sample blubber/muscle interface temperature from A–D channel 2 and store in variable v2
atod8 v3 'sample deep muscle temperature from A–D channel 3 and store in variable v3
atod8 v4 'sample water temperature from A–D channel and store in variable v4
pinhigh 1 'turn off FET to power down temperature circuits
plotbyte "Subcutaneous", v1, conv-temp1 'run conversion subroutine entitled conv-temp1 on the current A–D value in v1 and then save to memory the calibrated subcutaneous temperature in deg. Celsius
plotbyte "Blubber/muscle", v2, conv-temp2 'save to memory the calibrated blubber/muscle temperature
plotbyte "Deep muscle", v3, conv-temp3 'save to memory the calibrated deep muscle temperature
plotbyte "Water", v4, conv-temp4 'save to memory the calibrated water temperature
ifnotfull DATA 'check memory: if not full, then go to section DATA; if full, then drop below
display "FULL" 'display "Full" on the LCD
stop 'end data collection and put the data logger in lowest power mode
```

CONCLUSIONS

The adoption of the method presented here, i.e., to design appropriate data loggers based on a commercially available data-logger engine and, where possible, off-the-shelf sensor/transducers that were available with integrated conditioning circuits, has resulted in the timely production of remote monitoring instruments ideally suited for the research questions to which they were applied. A major advantage of this approach is that researchers can follow it simply by identifying and constructing the necessary sensor electronics and writing a simple program. This can be done with very little training in electrical engineering and computer programming and minimal assistance from a bioengineer or electrical engineer. Modifications of the designs presented here are presently in fruitful use in studies involving leatherback sea turtles, harbor seals, and Steller sea lions, and progress is being made on a similar data logger to be applied to another diving animal, human scuba divers. These data loggers, however, are not limited to use with divers but offer great potential for application to studies of comparative, environmental, or exercise physiology involving most medium-to-large animals, including humans.
I thank Don Croll and Cheri Recchia, who independently introduced me to the Tattletale line of computers, and Tony Lum, who taught me how to put them to work. I also thank Roger Hill for advice on data logger design; Don Brandys and Bruce Gillespie for help with construction; the staff at Onset Computer for answering all my questions; Dave J ones, Manfred Enstipp, and Amanda Southwood for reviewing an earlier draft of the manuscript and for participating in the evolution of the data loggers described here; Vicky Earle for the data logger illustrations; and my fellow graduate students and colleagues at the University of British Columbia and the University of California Santa Cruz who participated in the studies that made use of these data loggers.

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Address for reprint requests: R. D. Andrews, Dept. of Zoology, University of British Columbia, 6720 University Blvd., Vancouver, BC, Canada V6T 1Z4.

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