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Review

Genesis and evolution of bio-logging devices: 1963–2002

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Abstract: Bio-logging devices have become an integral part of many studies on the behavior, physiology and ecology of marine vertebrates. In the beginning, 1963, a time depth recorder (TDR) was designed to measure time and depth of freely diving Weddell seals, *Leptonychotes weddellii*, in the Antarctic. This was the first device used to obtain detailed information on underwater activity of an aquatic animal. It recorded data for one hour. Since that time there has been a steady evolution of this type of recorder. In 1975 a revised TDR with an extended time base of 14 days recorded the diving activity of the northern fur seal, *Callorhinus ursinus*. Through the rest of the 1970's and 1980's other fur seal species, as well as Weddell seals, and leather back sea turtles were studied, and the inventive pace of the TDR quickened. In 1981 an elegant mechanical recorder that lasted for three months was deployed. The emergence of microprocessors in the 1980's made possible further miniaturization and the logging of several additional variables. The next revolution occurred in the 1990's with the inception of satellite transmitters that made it possible to determine precisely where an animal was on the planet, and to retrieve other data as well. This remarkable ability to incorporate the measurement of spatial distribution was soon augmented by a third revolution, the use of mountable videocameras or camcorders on the animals themselves. With this arsenal of bio-logging devices many questions about aquatic animals are being resolved that were only dreams for the first generation of biologists studying the marine activities of vertebrates.

key words: archival recorder, bio-logger, camcorder, TDR, PTT

Introduction

Bio-loggers have become an integral part of nearly all studies on the behavior, physiology and ecology of marine vertebrates. A fundamental beginning was made during the mid-1800's with the invention of a depth gauge by William Thompson (a.k.a. Lord Kelvin), that when attached to a sounding line enabled ships to determine depth while underway. For the times this simple, capillary tube was of great practicality and Per Scholander adopted this means of recording depth in the 1930's to make the first depth measurements of a diving mammal (Scholander, 1940). In this case it was a harpooned fin whale, *Balaenoptera physalus*, making its last dive. After this time little was done until the 1960's when a time depth recorder (TDR) was designed and built out of uncomplicated, off-the-shelf items to add the behavioral context to some physiological experiments being conducted on Weddell Seals, *Leptonychotes weddellii,* in the Antarctic (Kooyman, 1965). Time was limited to one hour, but this was the first device used to obtain detailed information on underwater activity of an aquatic animal. At first there was a slow evolution of the recorder. By 1975 a totally revised TDR made possible the recording of the diving activity of fur seals and Weddell seals over 14 days (Kooyman *et al*., 1976). In 1981 a major time expansion occurred in the TDR when Yasuhiko Naito produced an elegantly constructed TDR that lasted for > 3 months (Naito *et al*., 1989). The inventive pace quickened in the 1980's with the emergence of microprocessors that made possible miniaturization and the logging of several additional variables with the incorporation of appropriate sensors. The size reduction made it possible to log the activity of birds as well as mammals and sea turtles. The species list of animals under study accelerated. Attachment became an important factor and special epoxy glues enabled the application of the units, now called loggers, to various species of animals. By the 1990's with the increased memory capacity of electronic recorders data were being collected over a period of several months, and the premier species in data saturation was the recording of the entire migratory cycle of elephant seals. Following is my story and perspective of how it all began and evolved.

Genesis

For a perspective of the state of field biology in the early 1960's, when the logging of data from marine animals at sea began, it is noteworthy that some of the most famous long-term studies of animals in their habitat had just begun. Most celebrated was Jane Goodall, who had just started her descriptions of social behavior of chimpanzees, *Pan troglodytes,* at Gombe. George Schaller had just finished his work on mountain gorillas, *Gorilla gorilla beringei*, near Mt. Virunga. E.O. Wilson was developing a host of concepts from his field studies of ants. Stephen J. Gould had yet to start his writing of the monthly piece for Natural History Magazine. As for me, I was interested in the forced submersion experiments of Irving and Scholander and wanted to take a new direction by conducting physiological experiments on freely diving marine mammals to place the physiology of diving in the context of their natural history. I was fresh from a 1961–62 field season in Antarctica, where I had met the Weddell seal and realized that it was the premier animal on which to conduct such studies. The vast ice area covering McMurdo Sound provided a platform for field work on a marine mammal that was unmatched anywhere. Initially my seals were restricted to an isolated dive hole. During these experiments my objective was to record a profile of time and depth for each dive that the seal made, but no suitable recorder was available.

I consulted with Howard Baldwin, a local Tucson, Arizona electronics engineer, who incidentally was building tracking transmitters for Schaller's work in the Serengeti, where he had moved on to after the gorilla study. Baldwin was not interested in doing the simple and cheap mechanical recorder that I had in mind and introduced me to a local watch repairman, Bernard Strothman. I presented him with my pressure gauge, kitchen timer and glass disks, and he set to work machining the parts necessary to put it all together at a cost that my small National Science Foundation budget could afford. Windup kitchen timers only run for an hour so that was the limit on duration of my TDR. Because of this limitation I was in close touch with the seals for the whole time that the recorders were deployed, and for the process of exchanging one recorder for another. The recorder worked extremely well. What I recorded during 1964 were not only the deepest and longest dives ever measured for marine mammals (Kooyman, 1966), but profiles of dives. These records led to hypotheses about how they tolerated pressure, remained submerged for so long, and how they found their way about under the ice. I spent the next 25 years pursuing studies on Weddell seals and other marine mammals.

Incubation

After another two seasons working on Weddell seals with an occasional diversion to study diving behavior of emperor penguins, *Aptenodytes forsteri*, when incidentally, we measured the first diving depths of a foraging bird (Kooyman *et al*., 1971), I spent the next few years doing diverse projects on other marine mammals and penguins. However, a return to free ranging dive studies was ever present in my mind, but a better recorder was needed and it would cost money. During that hiatus the US Marine Mammal Protection Act was passed into law. About that same time American oil interests were searching offshore in our coastal waters for new oil resources. Since marine mammals were now very much in the public's mind, and they were now protected by law, there was special concern about what an oil spill would do to them, especially sea otters and fur seals that relied on fur for insulation. At this time my closest scientific friend, Roger Gentry, was working for the National Marine Fisheries Service, Marine Mammal Laboratory. His primary work was on the breeding behavior of northern fur seals, *Callorhinus ursinus*, and guess what, the US government wanted to open the area around the Pribilof Islands to oil exploration. They approached Roger about a study of the effects of oil on temperature regulation in fur seals. Roger asked if I was interested. I was not especially interested in the physiology of oil effects on marine mammals. However, if they were willing to support, as part of the project, the development of a TDR that would cover the two week foraging period of nursing female fur seals then we might be able to make some exciting discoveries. They agreed and Minerals Management asked for a proposal. A short time later we had a contract. Timing could not have been better because soon after, Jim Billups, an eccentric master designer and artist in a machine shop, walked into my office and asked if I was looking for someone to build a TDR. I hired him on the spot. The first unit recorded on pressure paper and we deployed it on a northern fur seal female in the summer of 1975 (Kooyman *et al*., 1976). The retrieved record was beautiful in our eyes, but the paper format had to go. With grant help from the research arm of the Marine Mammal Commission we produced a film recorder and deployed it on south African fur seals, *Arctocephalus pusillus pusillus*, in January of 1976 (Kooyman and Gentry, 1986). With Billups building TDR's and coming up with new designs, my group went into a collaborative frenzy of behavior and physiology projects on various animals from sea turtles (Eckert *et al*., 1986) to elephant seals (Le Boeuf *et al*., 1986). We also began to consider electronic recorders so that we might reduce the size and mass to a suitable size for diving birds.

Radiation

One of the most inexpensive ways of recording data from aquatic animals were some very novel recording devices developed by Rory Wilson while he was working on South African Penguins, *Spheniscus demersus* (Wilson and Bain, 1984a, b). For the first time, as far as I know, the recording devices were being designed and used by someone other than a physiologist. Wilson was able to record swim speeds and depths on X-ray film. Small radioactive beads attached to the speed or depth sensor exposed film that was wrapped around the sensor. From these records he could determine the time spent at different swim speeds and at depth. The small size of the recorders now made it possible to work with the smaller penguins.

From Japan complex miniaturization of TDR's produced what can appropriately be termed works of art. In the hands of Yasuhiko Naito, working first on loggerhead sea turtles in 1981, and later on elephant seals and penguins, the amount of information on diving animals exploded. Naito's collaboration with Costa and Le Boeuf on northern elephant seals, *Mirounga angustirostris*, was one of the most successful (Le Boeuf *et al*., 1992).

In the late 1980's Paul Ponganis and his brother Ed came to my lab with questions, and ideas on how to answer them. Paul wanted to collaborate with me on physiological studies of seals and birds. This was an opportunity that provided an ideal match of skills and timing. As an anesthesiologist as well as having a PhD degree in marine biochemistry, Paul had the skills to manage the animals as well as the understanding to formulate excellent hypotheses. His brother Ed was an electronics engineer, and he built us some small recorders for us that, in addition to time and depth, included a heart rate recorder and paddlewheel for measuring swim speed. These were ideal for use on a large bird such as the emperor penguin, and I had in mind to use this bird in the isolated hole protocol the same way that I had studied the Weddell seal. Diving under ice was no more foreign to the emperors than it was for Weddell seals. When fenced off from the hole, they were frequently leaning hard on the gate trying to breakthrough to the water. The birds performed beautifully, and the information retrieved from the recorders opened new areas to explore in diving physiology (Kooyman *et al*., 1992).

By this time we had company in McMurdo Sound. Warren Zapol's team was pursuing studies of diving physiology on Weddell seals after having accomplished a series of experiments on forced submersion responses in the same species during the 1970's. To accomplish these objectives Roger Hill, a brilliant, young physicist, had joined the group, and he was responsible for designing a microprocessor controlled, submersible sampler/TDR that would record heart rate as well as draw blood samples (Hill *et al*., 1983). The radiation had begun

Table 1. Timeline of the first application: Maximum Depth Recorder (MDR), Time Depth Recorder (TDR), Logger, Archival Recorder (AR), Position Platfrom Transmitter (PTT), Satellite Depth Recorder (SDR), Popup Tag, Crittercam.

Type of recorder	Year	PI and affiliation	Reference of first publication
Capillary, MDR	1939	Scholander, Univ. Oslo	Scholander (1940)
MDR by TSK	1962	DeVries, Stanford	DeVries and Wohlschlag (1964)
TDR (1 h)	1964	Kooyman, Univ. Arizona	Kooyman (1965)
TDR (14 d)	1975	Kooyman, SIO, NMFS	Kooyman *et al.* (1976)
TDR (3 mo)	1981	Naito, NIPR	Naito *et al.* (1989)
Logger (24 h)	1981	Wilson, Univ. Cape Town	Wilson and Bain (1984a, b)
TDR-Heart rate recorder (hours)	1982	Zapol, Harvard	Hill *et al.* (1983)
PTT	1985	Bengtson, NOAA	Bengtson *et al.* (1992)
Popup tag (90 d)	1997	Block, Stanford	Block *et al.* (1998)
Crittercam (2 h)	1992	Marshall, National Geographic	Marshall (1998)

(for a summary see Table 1). Soon there were so many investigators using TDR's that it was impossible for any one researcher to know of all the diving studies in progress.

Not long afterwards Hill went into business making microprocessor TDR's, and I was one of the first in line to purchase some of his units to apply to my studies of king and emperor penguin foraging behavior during 1985 and 1986. Other companies appeared, but Roger's Wildlife Computers was one of the most successful. Once TDR's were readily available, diving studies proliferated in the 1990's (Fig. 1), and so did the sensors incorporated into the devices. There were temperature probes for measuring ambient temperature, temperature on or within various parts of the body, swim speed, heart rate, respiration rate, flipper stroke frequency, jaw or beak movement, accelerometers and light level for geolocation. TDR's, loggers, or archival recorders are now used routinely on a wide range of species.

By the 1990's another powerful technology became available that would revolutionize the type of experiments conducted on marine vertebrates and increase our knowledge of these mysterious animals greatly. The time for the application of space technology had arrived.

Argos receivers became operational on NOAA satellites in 1978. With the use of platform transmitter terminals (PTT) attached to the animal, a link with satellites orbiting at an altitude of 850 km made it possible to determine the location of a transmitter anywhere on the surface of the planet. The tool was powerful and the first to apply it to marine animals were John Bengtson and Roger Hill. They mounted the PTT on a crabeater seal, *Lobodon carcinophaga*, in the Antarctic Peninsula (Bengtson *et al.*, 1993). There was rapid acceptance of this tool by scientists in the marine vertebrate community. Again technological application proliferated throughout the world, and was used on just about every species that could tolerate the size of the transmitters. It was not long before the PTT's were also being deployed on birds (Davis and Miller, 1992). Most recently with the clever modification of a PTT and archival recorder Barbara Block has applied Popup tags to a species that pound for pound is

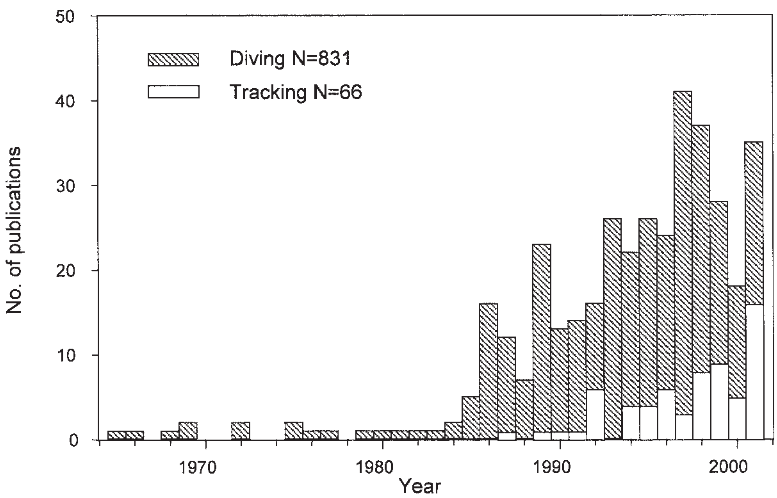

Fig. 1. Number of publications on diving studies and satellite tracking studies as indicated by an electronic search of BIOSIS, MEDLINE and Current Contents (figure courtesy of D. Costa).

the most commercially valuable animal in the sea (Block *et al*., 1998). Bluefin tuna, *Thunnus thynnus*, have now been tracked across the entire Atlantic Ocean basin with details of where they have been, sea surface temperature regimes frequented, and preferred depths. The marine top predator field had now advanced from detailed information on diving depths and a host of physiological variables, to broad information on migration patterns, type of habitats used, sex difference in these patterns, and most recently using animals as samplers of physical and biological oceanographic features. It is not surprising that at this stage a Hollywood-like application might arise.

At about the same time that the satellite tracking of marine divers began, Greg Marshall designed and built a mountable video camera that he called "crittercam". He conducted a pilot study in 1987 on a captive sea turtle. His first field deployment was in 1992 on Juan Fernandez fur seals, *Arctocephalus philippii*. The fur seal work became part of a popular National Geographic special, and now some of these top predators became direct agents for assisting the cinematographers and wildlife photographers confined to shore based operations. The mounted cameras obtained visual details of the world in which they live.

About this same time Randy Davis was developing a similar, but more data-intense camera, or camcorder system. In the mid-1990's he and Terrie Williams teamed up to deploy a camcorder on Weddell seals in Antarctica. The results provided, among other observations, some interesting insights into the tactics that the seals employ to catch fish. After these results were published in Science (Davis *et al*., 1999), the work was widely cited in the US press and the videotape obtained by a seal appeared on the nightly news. The Davis team had achieved what I once heard Carl Safina, a noted author on conservation books, advocate at a conservation conference. To paraphrase his words, "... after you have published your paper in the science journals, where a small group of people will read it, publish it in an outlet that will reach an audience of >50000 if it is to have a significant influence on protecting the species or its habitat".

Summary

In the course of this evolution and radiation of bio-loggers, emphasis in research has shifted from directly observable behavioral studies on land to unobservable behavior at sea. Wildlife at sea is no longer the deep mystery that it was 20 years ago, and many myths have been overturned. The list of examples is extensive. To mention a few: 1) Right whales, *Eubalaena glacialis*, are not just coastal and shallow in their sea sojourns, but often they are offshore in deep water (Mate, 2003). 2) White sharks, *Carcharodon carcharias*, are pelagic most of the time, and spend much of that period at depth, rather than nearshore around coastal marine mammal colonies. 3) Emperor penguins are not restricted to Antarctic waters. During their life cycle some commonly enter sub-antarctic waters (Kooyman *et al*., 1996). The results from bio-loggers have enabled us to develop hypotheses as diverse as hunting tactics, aerobic diving limits, central place foraging, and oceanographic associations. Perhaps in the end the widest and most significant application will be where questions go beyond physiology, behavior and ecology, to the conservation of the species. By obtaining information vital to a species such as their critical habitat, we may be making a contribution that exceeds the scope of our original objectives.

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