*RELATIONSHIP OF SLEEP, RESPIRATION, AND ANESTHESIA IN THE PORPOISE: A PRELIMINARY REPORT**

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Abstract.—The porpoise, an air-breathing mammal whose habits are entirely aquatic, presents special problems of respiration, sleep, and anesthesia. These problems have been studied in three species, *Tursiops truncatus*, *Lagenorhynchus obliquidens*, and *Phocoenoides dalli.*

The respiratory rhythm is unusual in that there is an extended pause—an apneustic plateau—between periods of expiration and inspiration. This rhythm has been observed under waking conditions, during sleep, and also when the animal is anesthetized. Two kinds of sleep behavior have been identified in *Tursiops* and *Lagenorhynchus.* In one of these, which is a light phase, the animal rests on the tank bottom for short periods, up to perhaps four minutes, and then comes to the surface to breathe. In a deeper phase the animal maintains itself at the surface for extended periods, breathing in an automatic fashion. In *Phocoenoides* no sleep behavior has been observed at any time.

I have examined the special theory of Dr. John C. Lilly regarding respiration and sleep in the porpoise, which is based upon the assumption that respiration in this animal is altogether voluntary, and from my observations have concluded that respiration in the porpoise can be automatic or can be brought under voluntary control, just as in other mammals. Also the anesthetization of this animal can be carried out safely by methods that correspond closely to those employed in other animals.

Introduction.—In collaboration with Professor E. G. Wever and Dr. Sam H. Ridgway since late 1965, I have been engaged in a study of hearing in the porpoise utilizing the method of cochlear potential recording. A humane procedure for anesthetization of porpoises for major surgery had not yet been perfected in 1965. To facilitate our experiments and to advance the basic medical care of the animals we wished to study, our first work was to define the basic anatomy and physiology of sodium thiopental and halothane anesthesia for major surgery in the porpoise.[1–4]

Before our experiments with porpoise anesthesia, there had been reports by several investigators of the anesthetic death of porpoises after unsuccessful attempts to anesthetize them, particularly with the barbiturates.[5–7] Much of this early work came from the laboratory of Dr. John C. Lilly. In a group of papers Dr. Lilly sought to account for the anesthetic deaths by principles derived from his studies of sleep behavior, eye movement, and the neurophysiology of respiration in the porpoise *Tursiops truncatus.*[8–11]

The present paper is a discussion and evaluation of Lilly's tenets concerning sleep, respiration, and anesthesia in the porpoise. It is a preliminary report, and will be followed by a more complete communication.

My observations are based on the anesthetization of 35 porpoises (*Tursiops truncatus* and *Lagenorhynchus obliquidens*), and the study of sleep behavior in two *Lagenorhynchus obliquidens*, seven *Tursiops truncatus*, and ten *Phocoenoides dalli*. Dr. Ridgway and I tested two *Tursiops truncatus* with trifluomeprazine (cf. ref. 33).

In collaboration with Dr. Jesse F. Crump of the Auditory Research Laboratories, Princeton University, Ridgway and I measured the respiratory response of a *Tursiops truncatus* to regulated levels of CO_2, O_2, and N_2. This experiment will be described in detail in a future communication.

A study of the optic nerve projections in *Lagenorhynchus obliquidens* by the Nauta technique was carried out in collaboration with Dr. Sven O. E. Ebbesson, Laboratory of Perinatal Physiology, National Institutes of Health, San Juan, Puerto Rico. Certain phases of this study are still in progress and will be reported later.

Lilly's Tenets of Sleep and Respiration in the Porpoise.—Lilly proposed three basic tenets concerning respiration and sleep in the porpoise—all of which are a departure from the principles of behavior and physiology of land mammals: (1) The inhibition of the act of respiration in the porpoise (*Tursiops truncatus*) is controlled at a thalamocortical level—more specifically in the nucleus ellipticus of the thalamus.[10] As a result of this neurological system, porpoises "lack our unconscious automatic, self-sustaining breathing system—this function (in porpoises) is almost if not fully voluntary."[8] (2) *Tursiops truncatus* does not breathe while asleep; instead, it wakes up in order to surface for each breath.[10, 11] (3) The porpoise sleeps with one eye closed at a time, to "assure that the animal is always scanning his environment with at least half of his afferent inputs."[10, 11]

In support of the first tenet above, Dr. Lilly referred to his observations that in barbiturate anesthesia porpoises lose control of respiration before they lose consciousness,[6, 7] and that electric stimulation of the nucleus ellipticus in the thalamus of the porpoise causes explosive respiratory acts to take place.[9] He further argued that "The adaptive value of an inhibition of respiration before loss of consciousness may have a high survival value, relating the respiratory event to a conscious knowledge of the state of the sea and possible nearby enemies such as sharks.[10]

Experiments and Discussion Relative to Lilly's Tenets.—Control of respiration: It is well known that the involuntary respiration of man and other land mammals can be driven by peripheral and central chemoreceptors that are responsive to changes in CO_2 and O_2.[12, 13] This phenomonon had never been tested in the porpoise, and I felt that the experiment would be particularly pertinent to Lilly's claim that respiration in the porpoise "is almost if not fully voluntary."

By presenting controlled mixtures of CO_2, O_2, and N_2 to a *Tursiops truncatus*, we determined that concentrations of 5 per cent CO_2 or greater caused an increase in respiration rate. At 5 per cent CO_2, the rate of respiration was double that measured with ambient air breathing. This held true even when O_2 was concurrently raised to 40 per cent.

Decreasing the O_2 to 9 or 10 per cent while holding the CO_2 at ambient level also caused a respiration rate double that measured in ambient air.

Our experiment seemed to indicate that O_2-CO_2 respiratory control in *Tursiops truncatus* is similar to that of other mammals, except that tolerance to CO_2 in the blood is greater due to increased buffering capacity. Normal average expired CO_2 for *Tursiops* is 6–9 per cent.

Respiration during anesthesia: When one observes the natural respiratory pattern of the awake porpoise, as described by Irving, Scholander, and Grinnell in 1941,[14] there can be no doubt that the porpoise has an apneustic respiratory mechanism that operates differently from the pons apneustic center of man.[15] Whereas man normally breathes continuously in and out, with pneumotaxic and apneustic brain centers opposing each other in sequence, the porpoise holds an apneustic plateau for 20 to 50 seconds between expiration-inspiration periods.

For most mammals during the induction of anesthesia, the control of the intercostal muscles involved in breathing is lost before the loss of diaphragm control; and diaphragm control alone is sufficient to maintain respiration without the work of the intercostals.[16] In contrast, my studies of anesthesia induction in the porpoise have demonstrated that the porpoise must utilize his intercostal muscles to maintain respiratory excursions, and he also must have control of his larynx and blowhole to help to maintain air in the lungs during the apneustic plateau. When sodium thiopental is administered intravenously as a preliminary to intubation of the porpoise, it is necessary to wait for the cessation of breathing. Before breathing stops, the porpoise has extremely good control of the closure of his epiglottis, and he can deliver a rather painful pinch should a finger be inserted in the larynx before it is completely relaxed. As the thiopental takes effect, the epiglottis relaxes and air escapes from the larynx, and concurrently the intercostal muscles may go into a momentary spasm of contraction. The problem of moving the intercostal muscles for the apneustic plateau is compounded for the porpoise by the added weight of his body when he is removed from the water. In recovery from anesthesia, the blowhole is the last element of the respiratory system to regain function.

Certainly the explanation for loss of respiration before loss of consciousness in the porpoise is not entirely one of a shift of brain-stem function to a thalamocortical level; neuromuscular problems must be involved. Furthermore, in contradistinction to the respiratory systems of land mammals, the porpoise may have a shift in the balance of brain stem pneumotaxic and apneustic centers which renders the system more susceptible to anesthetic depression. In a study of stimulation of the medulla oblongata in the cat, it has been found that pentobarbital anesthesia reduces the threshold for apneusis without rhythmic breathing. Also, pentobarbital is known to uncouple the elements controlling intercostal and diaphragmatic musculature.[17]

Sleep behavior: In his review of the neurophysiology of the states of sleep, Jouvet remarked that, "Indeed, there is no absolute behavioral or electroencephalographic criterion of sleep."[18] No one has yet studied the electrophysiology of sleep in the porpoise, but there exist in the literature two different behavioral descriptions of sleep in porpoises. On the one hand there is Lilly's aforementioned report that the porpoise wakes up and actively swims to the surface for each breath during sleep or cat-napping periods, and that the porpoise always sleeps with one eye open. On the other hand, there are several brief descriptions of a more passive sleep behavior in *Tursiops truncatus* and other *Cetacea*—a surface sleep involving only enough tail-fluke movement to ensure the elevation of the blowhole above the surface for each breath and to maintain a relatively stationary position on the surface of the water.[19–24] One article mentions that in this type of sleep the eyes remain closed on the average for 15 to 30 seconds.[19]

My observations of sleep behavior in the porpoise have revealed that each of the two descriptions outlined above is part of the story. Porpoises do both. Although it is not necessary that one phase precede the other, the porpoise usually first enters a phase of cat-napping on the bottom. Here the animal indeed has one or both eyes open, may blink his eyes alternately, and is responsive to the movement of observers and other animals in the tank. When not disturbed, the animal spends approximately four minutes on the bottom in this posture, swimming actively to the surface to breathe at the conclusion of each four-minute period and slipping back down again, tail first, to the bottom after several respiratory cycles at the surface.

The cat-napping behavior may or may not lead to a second phase of activity, in which the animal assumes a position at the surface of the water. In the early stage of this phase the porpoise may periodically open one or both eyes. Tail movement takes place in coordination with respiration. One animal studied in this state reacted with a previously learned response to a command to swim to an observer.

As this phase continues, in calm water with no interference from people or other animals, the tail movement subsides, the animal floats at the surface with the blowhole exposed for respiration, and both eyes remain closed for periods as long as one hour. The animal is not responsive to observer movements outside the tank or to the movement of other animals in close proximity. One animal in this state made no response to a flash camera, and another failed to give the previously learned response to a command to swim to an observer.

In addition to the above two phases of sleep activity, a porpoise has also been observed to make extended "motionless" glides under water with one or both eyes blinking. The awareness state here can thus far only be defined in a manner similar to that presented for cat-napping behavior.

Whereas Lilly found his observations of active conscious respiration during sleep to be in accord with his theory of thalamocortical respiration in the porpoise, the observations of surface sleep behavior that I have made do not require postulating such a mechanism. In fact, the respiratory pattern of the porpoise during surface sleep is automatic in nature, not involving active swimming to reach the surface for breath.

With conjugate eye closures during surface sleep for up to one hour, the porpoise is obviously not "always scanning his environment with at least half of his afferent inputs."

Moreover, I have found that independent eye movement is not unique to the cat-napping behavior described by Lilly. In the awake state, in or out of the water, I have noted that *Tursiops truncatus* frequently moves his eyelids independently. *Tursiops* may be seen to close one eye to avoid direct sunlight while the eye toward the shade is fully open. An animal on a stretcher may look down and forward with one eye, while looking up and backward with the other.

If during sleep the porpoise were scanning his environment with only half of his visual afferent inputs, the implications would be interesting. A Nauta eye enucleation study which we are carrying out on *Lagenorhynchus obliquidens* points toward confirmation of Hatschek's observation that in the porpoise the optic nerve appears to cross completely at the optic chiasma.[25] This would mean that information received by one eye during sleep would be sent solely to the contralateral occipital cortex and cross to the ipsilateral hemisphere via pathways such as the corpus callosum.

Behavior with trifluomeprazine and anesthesia: Schevill *et al.* lent credence to Lilly's theory of voluntary respiration in the porpoise by noting that "the use of presently known drugs (central nervous system depressants) to immobilize an aquatic mammal (especially porpoises) in the water is almost certain to kill the animal by suffocation, either by allowing it to sink or by stopping breathing, or both."[26]

With doses of 1-mg/kg trifluomeprazine (racemic-10-(3-dimethylamino-2-methylpropyl)-2-trifluoromethylphenothiazine, manufactured by Norden, of Lincoln, Nebraska) we have been able to tranquilize *Tursiops truncatus* without a depression of respiration and without having the animal sink to the bottom of his home tank.[27]

The behavior during depression of consciousness of a *Tursiops truncatus* proceeds much like that which I have described for surface sleep. About half an hour after the intramuscular injection of trifluomeprazine, the animal stops swimming about the home tank and assumes a stationary position at the surface of the water, similar to the position during sleep. The animal's tail hangs down toward the bottom of the tank and the blowhole just breaks the surface of the water. The tail keeps up a slow rhythmic excursion in coordination with the breathing cycle—one respiration every 30 seconds. During the first half-hour of this activity the animal's eyes (one or both) open spontaneously, for brief periods. The eyes also open if the animal's thorax is touched.

About an hour and a half after the injection, the tail movement of the animal subsides, except for a gentle stroke of the tail with each respiration. Both eyes will remain closed for two hours or more, and they do not open when one gently touches the animal. In 24 hours, recovery from the trifluomeprazine is complete.

Body movements during the induction and recovery phases of anesthesia are also similar to those observed in surface sleep. With intravenous sodium thiopental induction, the action may take place too rapidly to be observed fully. However, with induction utilizing a two to three per cent concentration of halothane, the animal goes through a period of "swimming movements" of the tail fluke—with excursions of 1 to 2 feet at first, diminishing to a quiescent state as a surgical plane of anesthesia is obtained. The reverse occurs upon recovery from anesthesia.

When a surgical plane of anesthesia is reached, the tail movement stops. The bradycardia associated with the apneustic plateau in normal porpoise respiration is abolished with the onset of anesthesia, and the heart rate becomes regular with a normal electrocardiogram. Considering this phenomenon in the light of Richet's observation that the bradycardia of diving animals can be eliminated by cutting the vagus nerves or by administering atropine,[28] I believe that a medulla-brain stem depression is indicated during anesthesia in porpoises.

The Dall Porpoise.—The foregoing discussion of *Tursiops truncatus* and *Lagenorhynchus obliquidens* raises questions concerning Lilly's basic tenets of sleep, respiration, and anesthesia in the porpoise. Further exploration into the electrophysiology, neuroanatomy, pharmacology, physiology, and behavior of porpoises is obviously needed for a complete understanding of all the parameters involved.

Another fascinating research challenge is presented by the Dall Porpoise, *Phocoenoides dalli* (True). In the study of the behavior of ten captive animals of this species, there has never been any observation of activity resembling sleep behavior. There is neither cat-napping nor surface sleep.

In some way this fact must be related to the unique physiology of the Dall Porpoise, which has already been observed. In comparison with *Tursiops truncatus* and *Lagenorhynchus obliquidens*, the Dall Porpoise has a smaller brain,[29] different ecology, better anatomical adaptations for deep diving and faster swimming, comparatively large adrenal glands,[30] higher food consumption, thinner blubber, larger heart size and blood volume,[31] hemoglobin with different electrophoretic characteristics, and an oxygen dissociation curve that gives the animal a special advantage in deep dives.[22]

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