# Hearing deficits measured in some *Tursiops truncatus*, and discovery of a deaf/mute dolphin

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Eight bottlenose dolphins *Tursiops truncatus* (four male, four female) were trained to respond to 100-ms tones. Three male dolphins (ages 23, 26, and 34) exhibited hearing disability at four higher frequencies—70, 80, 100, and 120 kHz even at 111–135 dB *re*:1 $\mu$Pa. Two females (ages 32 and 35) responded to all frequencies as did a male (age 7) and a female (age 11). One female (age 33) responded to all tones at 80 kHz and below; however, she failed to respond at 100 or 120 kHz. One young female dolphin (age 9) exhibited no perception of sound to behavioral or electrophysiological tests. This young female was not only deaf, but mute. The dolphin was monitored periodically by hydrophone and daily by trainers (by ear in air) for 7 years until she was age 16. The animal never whistled or made echolocation pulses or made burst pulse sounds as other dolphins do. [S0001-4966(97)02812-9]

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## INTRODUCTION

Audiograms have been done on several species of the cetacean superfamily Delphinoidea (Au, 1993; Richardson, 1995). Most of these species are represented by only one or two young animals. All of these animals, with the exception of one killer whale, *Orcinus orca* (Hall and Johnson, 1971), had good sensitivity from 60–120 kHz. The first detailed audiogram of the bottlenose dolphin, *Tursiops truncatus*, yielded a threshold of 42 dB *re*: 1 $\mu$Pa ($10^{-14}$ W m$^2$) at 60 kHz with about a 20-dB increase at 120 kHz and a very steep increase thereafter, to a maximum of 150 kHz (Johnson, 1967). Johnson's animal was 9 years old.

During an acoustic response time task (Ridgway *et al.*, 1991), we tested the hearing of eight *Tursiops* (four males, four females) at levels that were expected to be 60–80 dB above threshold, based on earlier delphinoid audiograms mentioned above. One of our experimental dolphins, a male aged 26, had been tested 13 years earlier by Ljungblad *et al.* (1982). The animal had been shown to have good hearing at this earlier date. Although this dolphin (IAY), at age 13 in the early 1980s, had thresholds 5–10 dB higher than the male age 9 used by Johnson (1967), Au (1993) has pointed out that this difference could possibly be accounted for, in part at least, by the differences in test methodology.

Until we first presented this at the Denver meeting of the Acoustical Society (Ridgway and Carder, 1993a), no tests of hearing had been done with older (>25 years) dolphins of either sex. During the past 33 years with the Navy marine mammal program, we have observed sound production and some related behavior in about 200 bottlenose dolphins (cf. Ridgway, 1983). Recently, we had the opportunity for the first time to observe a dolphin that was both deaf and mute.

## I. MATERIALS AND METHODS

Age and sex of each of the experimental dolphins are given in Fig. 1. The oldest male was age 34 at the time of the test and had been with our laboratory since 1962. During the 1960s and 1970s, he had demonstrated apparent good hearing and echolocation ability, although an audiogram had never been done. Health and medication records were kept on all the dolphins since their initial acquisition or birth. Among the animals we tested, records on animal MAU, for example, go back to 1962. The potential for ototoxicity has always been a consideration for dolphin medication, however, two of the animals had received aminoglycosides (Anon, 1994) for infections. Animal MAY was given genta-mycin (600 mg twice daily) for seven days in 1980, six years prior to the hearing tests. Dolphin SLA was given one injection of penicillin/streptomycin in 1968 and a single injection of amakacin and penicillin G in 1992.

The dolphins listed in Fig. 1 were trained to whistle or burst pulse when a stimulus tone (St) was delivered through an underwater hydrophone located 1 m in front of the animal. This training was similar to that reported previously (Ridgway and Carder, 1988; Ridgway *et al.*, 1991). We noticed that when a dolphin whistled, there was a characteristic movement along the left posterior margin of the nasal plug of the closed blowhole. Burst pulse sounds generally resulted in a somewhat different movement, more to the right side of the dolphin's blowhole. Our trainers quickly induced dolphins to repeat vocalizations by tapping with a finger or manipulating the area of the blowhole where movement or any escaping air concurrent with sound had been detected. After whistles or burst pulse sounds were reliably elicited in this manner, the signal was transferred slowly to a simple stroke to the dolphin's melon. Then, with the dolphin underwater in front of the trainer, the melon stroke was paired with a tone until the animal reliably gave the vocalization each time the tone was presented through the hydrophone.

The animals were trained to station on a plastic bite plate 1.0 m underwater and remain stationary until an underwater buzzer (bridge or S2 signal that informs the animal that a fish reward will soon follow) was sounded. Initially,

**HIGH-FREQUENCY RESPONSE OF EIGHT TURSIOPS
TO A 100 ms TONE STIMULUS OF 111 dB re 1 μPa**

| Animal | Sex | Age | Stimulus Frequency (kHz) | | | | |
|--------|-----|-----|------|------|------|------|------|
| | | | 40 | 60 | 80 | 100 | 120 |
| MAU | ♂ | 34 | ▲ | △ | △ | △ | △ |
| MKA | ♂ | 23 | ▲ | ◮ | △ | △ | △ |
| IAY | ♂ | 26 | ▲ | ◨ | △ | △ | △ |
| NAY | ♂ | 7 | ▲ | ▲ | ▲ | ▲ | ▲ |
| TOD | ♀ | 35 | ▲ | ▲ | ▲ | ▲ | ▲ |
| SLA | ♀ | 33 | ▲ | ▲ | ◮ | △ | △ |
| BRT | ♀ | 32 | ▲ | ▲ | ▲ | ▲ | ▲ |
| SAY | ♀ | 11 | ▲ | ▲ | ▲ | ▲ | |

▲ > 90% Responses
◨ > 75% Responses
◮ > 50% Responses
△ < 5% Responses

FIG. 1. The animal identifier, sex, age, and indication of correct responses to 100-ms, 111-dB tones for eight bottlenose dolphins *Tursiops truncatus* employed in this study.



**TURSIOPS HIGH-FREQUENCY RESPONSE**

♂ Salty @ Age 9      ◉ Response Threshold
♂ IAY @ Age 13      ● Response Threshold
♂ IAY @ Age 26      △ No Response
                          ◮ > 25% Responses
                          ◨ > 50% Responses
                          ◨ > 75% Responses
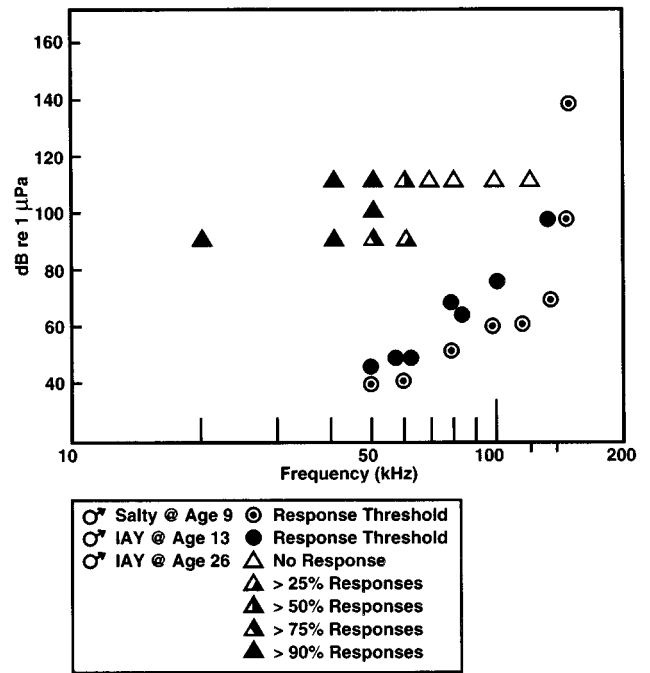                          ▲ > 90% Responses

FIG. 2. Responses of two bottlenose dolphins to high-frequency tones. Points (circles with dot) for Salty at age 9 from Johnson (1967), points (filled circles) for IAY at age 13 from Ljungblad *et al.* (1982). All triangles from present study.

the dolphin was given an S2 and rewarded each time it vocalized after a tone. Gradually the reward schedule was reduced until the animal made up to 20 responses in a row. The S2 was given immediately after the last correct vocal response in the series. The S2 was followed by a reward of one to several fish when the dolphin returned to the surface to breathe. The longest period the animal was required to remain on the underwater station was two minutes; however, both the time the animal was required to remain on the underwater station, and the number of tones presented during this time were varied in a random fashion. For catch (no stimulus) trials, the dolphins were sent down to the station but no tones were presented. After the dolphin had remained stationary and silent for periods varying between 30 and 120 s, the S2 was given and the animal surfaced for reward. Improper responses, i.e., leaving the station before the S2, vocalizing prior to or in the absence of the stimulus, or giving the wrong vocalization, were not reinforced with fish.

A trial series or testing dive (TD) was started when the trainer signaled the animal to go down to the plastic bite plate 1.0 m under the surface (Fig. 2), and 1.0 m from the stimulus hydrophone (an F42B for frequencies of 5–70 kHz; an LC-10 for frequencies of 80–120 kHz). During the earlier stages of training, 20% of the TDs were catch trials which were inserted randomly in the series of TDs. When the false alarm rate decreased to 5% or less of the correct response level, catch trials were reduced to 10% of TDs.

Tone stimulus (St) duration was 100 ms with a 2-ms gradual rise in intensity at onset and decline on termination. The findings of Johnson (1968) suggested to us that this duration was adequate. With three of the older males, some tests were done with 300- and 450-ms tones. Frequencies were 5, 10, 20, 40, 50, 60, 70, 80, 100, and 120 kHz. Stimuli were 111 dB, increasing in 6-dB steps to 135 dB in cases

where the animal did not respond to the baseline level. With the dolphin at 1.0-m depth and 1 m from the St hydrophone (Fig. 2), the trainer waited a variable period then pushed a switch starting a randomly variable St block. The computer selected Sts from a file in random initial delay and interval (1.1–2.1 s in 0.1-s steps) and offered Sts via a St generator as long as the trainer held the switch button down. Thus, the trainer could give several Sts in a row in the randomly variable sequence from the computer file, then let up on the switch and interpose a period without Sts before pressing the switch again for more Sts. Randomness in St delivery was maintained both by the computer program and by the trainer's switch press out of sight of the dolphin. Animal responses (ARs=whistle or burst pulse) were received by another hydrophone, digitized, and stored for confirmation of correct response. Each AR file with 20–200 Sts was edited on a CRT display of a 700-ms St window. No-AR trials, noisy trials, and wrong ARs were identified, and a database was constructed. The baseline stimulus of 111 dB *re*: 1 μPa generally exceeded background noise in San Diego Bay by about 50–80 dB in the 60–120 kHz range (also see Au *et al.*, 1985).

In addition to attempts at applying the above procedures, the apparently deaf dolphin SIB was trained to respond to a 45-kHz underwater locating beacon[1] (model DK355L), a ''pinger'' that was lowered into the water. The source level of the pinger was 160 dB *re*: 1 μPa and it produced one 10-ms pulse each second. After the animal had learned to take fish from the trainer's hand, the pinger was dipped into the water and the animal was rewarded for approaching it.

Gradually, the animal came to the pinger whenever it was put into the water.

Further, hearing of SIB was tested by evoked potential audiometry (Ridgway *et al.*, 1981). Tones and clicks at various intensities, repetition rates, and durations were presented via the same hydrophones mentioned above and positioned both 1 m in front of the animal and adjacent to the lower jaw, or attached by suction cup to the lower jaw (Moore *et al.*, 1995).

## II. RESULTS

### A. Responses of eight hearing dolphins of various ages

Results were obtained from the eight dolphins at various frequencies between 5 and 120 kHz (Fig. 1). At the baseline level of 111 dB *re*: 1 $\mu$Pa, all dolphins responded at better than 90% correct responses to frequencies of 5, 10, 20, 40, and 50 kHz, with the exception of one old male, MAU, that dropped to just over 50% at 50 kHz, 111 dB. The results at frequencies of 60, 70, 80, 100, and 120 kHz varied considerably between the different animals. One female and three male dolphins under age 20 at the time of testing and two females over the age of 30 demonstrated a capability for responding to all the frequencies at a correct response rate over 90%, and most over 95%. All of the males over age 23 showed varying degrees of inability to respond to tones of 60 kHz, and above.

The degree of hearing deficit with respect to frequency varied somewhat in the three old males and the one old female that demonstrated a hearing deficit. One male, IAY, responded consistently to tones of 60 kHz but responded to no tones of 70 kHz, and higher even when St duration was increased to 450 ms. The single old female that demonstrated a hearing deficit, dolphin SLA, also had a sharp hearing cut-off but at a higher frequency of 100 kHz. Two older males had a more gradual or incomplete hearing deficit. At 70 kHz, MKA responded to >75% at 135 dB and >50% at 129 dB but was <5% at 111 dB. At 80, 100, and 120 kHz, his correct response level dropped to less than 5% (near false alarm rate) at all intensities under 135 dB *re*: 1 $\mu$Pa, and at this level his correct performance was just under 25%. Correct response level was not increased significantly when tone duration was extended to 300 ms.

Figure 2 shows thresholds at the higher frequencies of a male dolphin age 9 (Salty) studied by Johnson (1967) compared with IAY at age 13 (Ljungblad *et al.*, 1982), and our findings on IAY at age 26 when the dolphin failed to respond to tones 40–50 dB above his threshold established by Ljungblad *et al.* (1982) 13 years earlier.

### B. Behavioral observations of the deaf dolphin (SIB)

The first unusual behavior was noticed soon after SIB was brought to our facility in San Diego Bay. We noticed that when SIB was apparently asleep, she adopted a posture that was different from any dolphin we had ever observed. We called this a ''spar buoy'' posture since the dolphin's rostrum was pointed straight overhead, and its tail hung straight down as the animal bobbed in the water.

Most dolphins in our program are trained to respond to a pinger or other acoustic device. This facilitates movement of animals around our dolphin pod complexes, and the pinger is used as a recall device when the animals are released in the bay or in the open sea. During initial training, soon after the dolphin was collected in the Mississippi Sound in 1984, SIB along with six other dolphins in her group appeared to respond normally when the pinger was dipped into the water. After the task was moved into the open bay, when SIB was away from other dolphins, and, especially as the distance over which the dolphin was required to respond was increased, trainers began to suspect that SIB was relying on vision instead of hearing the sound of the 45-kHz pinger. When SIB was separated from other dolphins in the group, and the pinger was inserted in such a way that the dolphin could not see the action, she did not respond.

### C. Other tests of hearing and sound production for SIB

Next, our trainers tried to elicit sound from SIB by the methods mentioned above. Neither whistles or burst pulse sounds could be elicited. The only sounds made by SIB were low Bronx cheer like sounds as the nasal plug fluttered during forced exhalations through a partially open blowhole.

We had noticed that when dolphins are separated from their group, they sometimes increase the rate of vocalization, especially the production of whistles. Twice, SIB was placed in a portable netting enclosure 5×4×3 m and slowly moved away from the group in San Diego Bay. Sound was monitored continuously by hydrophones (B&K 8103 with a B&K charge amplifier, and a Racal tape recorder with a frequency response at least as high as 150 kHz) for 3 h during each period of separation. No whistles, burst pulses, or echolocation pulses were recorded.

Finally, we attempted the electrophysiological approach which we have applied in the past to screen hearing in more than a dozen dolphins (Seeley *et al.*, 1976; Ridgway, 1980; Ridgway *et al.*, 1981). With both tone and click presentations from 1–120 kHz from hydrophones attached to the lower jaw, near the lower jaw, or in the water in front of the dolphin, no auditory evoked potentials were obtained, even to stimuli as high as 141 dB *re*: 1 $\mu$Pa.

## III. DISCUSSION AND CONCLUSIONS

Humans underwater can hear very high frequency tones by bone conduction (Deatherage *et al.*, 1954; MacKay, 1984), but there is no pitch discrimination above 15 or 20 kHz or above that person's hearing range. It would be interesting to know if the two older male dolphins, MAU and MKA, that showed some responses to the highest intensity tones (135 dB), retained any pitch discrimination at the frequencies from 60–120 kHz.

Although two out of four of our dolphins with hearing deficits had been treated with aminoglycosides for infections during their many years with our program, the short course of treatment, and the presence of normal kidney function as

indicated by clinical screens, suggest to us that such treatment did not cause the high-frequency hearing loss we observed.

Because a high percentage of the human population (males more than females) show hearing loss with age (Ries, 1982), it should not be surprising that other mammals share this deficit. Although our older dolphins with high-frequency hearing loss produce echolocation pulses, we have not studied them in echolocation tasks. We suspect that echolocation requiring fine discrimination in the presence of noise would be degraded. Au (1993) has shown that in Kaneohe Bay, where background noise in the 20–100 kHz range is dominated by snapping shrimp, dolphins shift their echolocation click peak frequency above 100 kHz. Our old dolphins with high-frequency hearing deficits would likely be at a disadvantage in such an environment.

For our old dolphins, survival is not dependent on the use of echolocation in the sea. *Tursiops* do survive in the wild to advanced ages. One extreme example of a female estimated to be age 52 has been reported (Scott *et al.*, 1996). We suspect that high-frequency hearing loss may well be a consequence of dolphin aging in the wild as well.

Although dolphin hearing and echolocation characteristics have received much more attention than other sensory abilities (cf. Au, 1993), *Tursiops* has good vision, some chemoreception, and good tactile senses (Nachtigall, 1986). The sense of touch is especially well developed (Ridgway and Carder, 1993b). After we determined that SIB was deaf, it became apparent from observing the dolphin's behavior that she had become adept at employing the other dolphins in the group to derive information that the others all received by the acoustic sense. For example, when the recall pinger was placed in the water, she probably became immediately aware of it by observing the behavior of other dolphins. Only when SIB was removed from the immediate presence of other dolphins, and the pinger insertion hidden from view, did we determine that the dolphin could not hear the pings.

When SIB was collected from the Mississippi Sound (Cat Island near Gulfport, MS) in 1984, she was a robust and apparently healthy animal within the weight range expected for the population (Ridgway and Fenner, 1982), We suspect SIB was able to survive, and maintain good nutrition not only by using senses other than audition, but by observing other dolphins. The mutual survival benefits of dolphin schools have been discussed by several authors (Norris and Dohl, 1980; Connor and Norris, 1982; Bradbury, 1986; Würsig, 1986).

We showed that dolphin calves produce echolocation pulses by about 60 days of age (Carder and Ridgway, 1984); however, we have recorded shrill whistles from calves within ten minutes after birth. Because SIB produced none of the usual dolphin sounds, we suspect that she may have developed deafness near or even before birth.

We do not know whether the unique ''spar buoy'' resting and sleeping posture of SIB was related to deafness or vestibular dysfunction. We noted this unusual behavior at the outset; however, we did not immediately suspect deafness. We now surmise that the unusual posture may have been related to the deaf and mute condition. Among the possible causes for her condition are infections. Severe infections can damage the vestibular system as well as the cochlea. A generalized infection affecting the cranium and nasal sinuses such as meningitis could result in such damage. When these dolphins with hearing loss die, histologic examination may shed light on the cause of this deafness.

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