Sound transmission in the spermaceti complex of a recently expired sperm whale calf

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Abstract: Sound pulses were projected into the forehead of a neonate, female sperm whale that died following a stranding and attempts to revive it. Two hydrophones, held against the skin, recorded the sound pulses and their reflections. A consistent reflection was found about 0.8 ms after sound projection. This time corresponded to the expected two-way travel time back and forth within the spermaceti organ. Reflections were also detected at the frontal surface of the junk from sounds projected into the distal sac area. These signals must have traversed rearward along the axis of the spermaceti organ to the frontal sac where they were likely reflected and directed forward to the front of the junk, demonstrating an acoustic continuum between the spermaceti organ and the junk. These results support the basic Norris and Harvey (1972) theory of sound generation in sperm whales and later amendments to that theory (Møhl and Amundin (1991), Møhl (2001)).
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1. Introduction

The grossly enlarged forehead (nose) of the sperm whale *Physeter macrocephalus* has been proposed to function as a generator of sound by Norris and Harvey (1972). Although still contested (Watkins and Daher, forthcoming), the basic Norris and Harvey concept has, over the years, received support from a variety of evidence (e.g., Møhl and Amundin, 1991; Gordon, 1991; Cranford, 1999; Møhl et al., 2000; Møhl, 2001; Ridgway and Carder, 2001). The basic concept involves only the monkey lips, the spermaceti organ, and the two air sacs (the frontal and the distal sac) in the generation and transmission of the multipulsed sperm whale click. Later, the so-called 'junk' compartment (junk is a whaler's term for the connective tissue with spermaceti bodies below the spermaceti case) has been suggested to be part of the internal sound path and the main exit of sound from the forehead complex (Møhl and Thiele, 1983 (Figure 1); Cranford, 1999; Møhl, 2001).

     A stranding of a neonate sperm whale near Kona, Hawaii on August 11, 2001, provided us with an opportunity to further study how sound travels within the forehead of the

whale by projecting sound and recording the reflections. The only previous transmission experiments of this kind (Møhl, 2001) were carried out on an adult male, using a monostatic approach (i.e., having transmitter and receiver so close to each other that they could be regarded as having the same position). This approach was found to have limitations with regard to implication of the junk in the sound path. With the Kona stranding, it became possible to use a bistatic approach (separation between transmitter and receiver) in parallel with the monostatic approach to get a physiological handle on the question of the involvement of the junk. In addition, size-related effects were studied.

2. Material and methods

The subject, a 3.12 m newborn, stranded, female sperm whale was temporarily housed in a 1.2 x 6 m temporary pool with seawater at the nearby Natural Energy Laboratory, Kona, Hawaii. Its status as a neonate calf was confirmed by an umbilicus not yet completely healed. It had been stranded the day before and taken to the nearby Natural Energy Laboratory in an attempt to begin rehabilitation. The calf received dedicated veterinary attention the entire time. Despite all attempts to save it, the calf died. It had been dead for about 20 minutes when sound transmission studies were initiated. The whale was floating with the head barely submerged. The sound-generating equipment consisted of a PC-controlled digital to analog converter, generating trains of pulses (pings) with a repetition rate of about 30 pulses/sec. Each pulse was a single period of a 15 kHz sine wave, led via a Haffler P3000 power amplifier to a J9 transmitter. The transducer's transmitting surface was held against the head of the calf (see figures below). The nominal, broad band source level was 149 dB peRMS re. 1 µPa. The spectrum of the recorded pings had a positive slope of about 3 dB / octave in the range of 5 to 20 kHz. The time/frequency properties of the pings approximated those of the main pulse in the adult sperm whale click (Madsen and Møhl, 2000).

The receiving end consisted of two B&K 8103 hydrophones. Their signals were amplified 18 – 24 dB by a specially built, multi-channel pre-amplifier and recorded on a Sony TCD-3 DAT recorder at a digitization rate of 48 kHz. The DAT-recording was subsequently transferred to CD-ROM, preserving the original digitization. A reflection, onset delayed 12 ms from the emission of the pings and with duration of several ms, is ascribed to reflections from the side of the tank. The delay value is somewhat large, compared with the expected, shortest two-way travel time across the tank (8 ms), indicating a less direct path. Reflections from the bottom of the pool and the surface were not identifiable. The aperture of the J9 is about 10 cm. The predicted directional pattern at 15 kHz is omnidirectional within 3 dB out to ±90°.

The transducers were handheld against the surface of the cadaver. One hydrophone was always set next to the J9 (≤ 1 cm), and is referred to as the monostatic hydrophone. The other hydrophone was placed at a distance about 16cm from the first one in most experiments. It is referred to as the bistatic hydrophone. Two frontal sites of excitation were chosen: at the distal sac and at the junk, *ad modum* Møhl (2001), with the bistatic receiver at the alternate site of that being stimulated. A number of additional experiments (with the bistatic receiver near the angle of the mouth, at the crest of the frontal bone, and halfway between the front and rear end of the head) have not been analyzed in detail, since the signals could not be separated in tissue- and waterborne sound. Software for analysis was CoolEdit 2000 and MatLab 5.3. A MatLab routine was adapted to extract individual pings and generate waterfall plots of the log of the envelopes of the time series. The envelopes were derived by Hilbert-transformation of the extracted ping events, covering about 4 ms. Due to the transducers being hand held, the recording geometry was not stable, preempting averaging techniques. All time series were normalized with respect to amplitude.

3. **Results**

The distance between distal and frontal sacs was estimated to be 55 cm, based on a photograph of the partly dissected head. Using a value for the velocity of sound in the spermaceti of 1.37 m/ms (Flewellen and Morris, 1978), a wavelength at 15 kHz would be around 9 cm. Accordingly, the length of the organ will be some 6 wavelengths, whereas the cross-section would be 1 to 2 wavelengths.

The predicted delay for two-way transit of the spermaceti complex is 0.8 ms. An example of the waveforms generated by a single ping is presented in Fig. 1. Here, sound has been injected at the distal sac and recorded next to the transmitter (monostatic), as well as at the junk (bistatic).
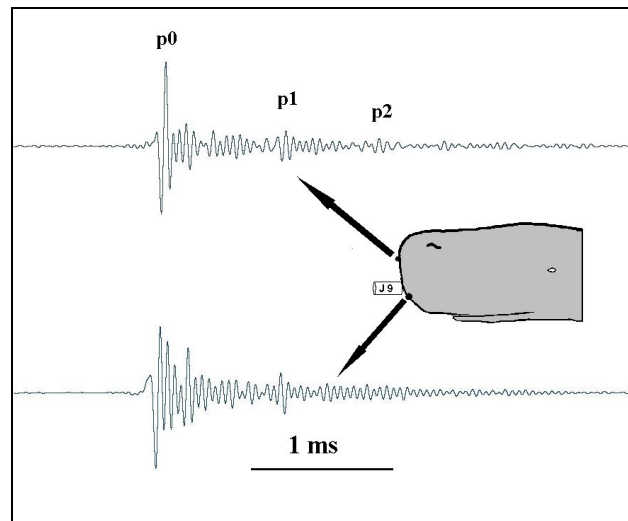

Figure 1. Waveform of ping, received next to the transmitting transducer at the distal sac (upper trace, monostatic) and at the junk (lower trace, bistatic). Insert shows position of the transmitter (J9) and the two receivers (filled dots). Pulses labeled according to Møhl (2001).

p0 signifies the directly received ping. The following numbered pulses represent back-and-forth reflections within the nasal complex, with some possible contributions from the nearby water surface and anatomical structures. Across the entire material, the higher numbered pulses vary in how well they stand out from the background. Some ringing from the J9 is consistently present in traces from the monostatic hydrophone, often obscuring the reflection pattern. To illustrate constant and varying features, pairs of waterfall plots of the envelopes (in dB) of about 100 consecutive pings are presented below for each stimulation site. In this format, subsequent envelopes are stacked along the y-axis, with time and amplitude along the x- and z-axis, respectively. Fig. 2a shows the monostatic condition: sound was projected into the junk; the receiver was next to the J9 transmitter. The first, most powerful peak is the directly transmitted signal, p0. It is trailed by 4 minor peaks of decreasing amplitude before the occurrence of another major peak, p1, delayed 0.8 ms from p0. In the 6 ms interval trailing p1, another set of minor peaks is seen, then a small but consistent double-peak (labeled p2$^?$) at –20 dB is detectable, delayed 0.7 ms relative to p1.

Fig. 2b shows the bistatic situation of the same series. Again, 4 minor peaks can be counted in the interval between p0 and p1, and this closely spaced peak pattern repeats itself in the interval between p1 and p2. The p0 - p1 interval is 0.8 ms; the p1 – p2 interval is 0.7 ms. The decay of amplitude from p0 to p1 is about 15 dB.
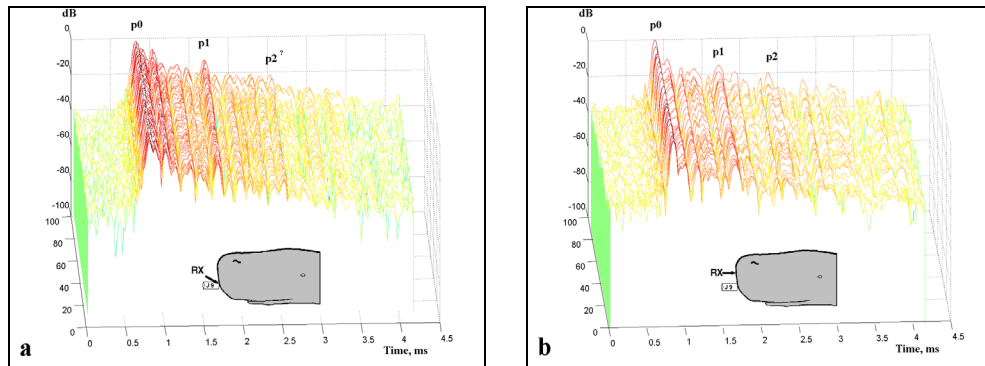
Figure 2. Waterfall plot of ping envelopes, stimulating at the junk (J 9). **a** Receiver (RX) at junk (monostatic case). **b** Same series, receiver at distal sac (bistatic case).

Stimulating at the distal sac (Fig. 3a and Fig. 3b) gives a similar pattern, but the pulse identification is ambiguous in the monostatic case (Fig. 3a). The p0 – p1 interval is 0.8 ms, with 4 minor peaks, the amplitude of the possible candidate for p1 being 22 dB below the level of p0. In the bistatic case (Fig. 3b), 3 minor peaks occupy the 0.8 ms interval between p0 and p1, repeated in the p1 – p2 interval. The latter lasts 0.75 ms. The decay rate of the amplitude of consecutive pulses is about 10 dB.
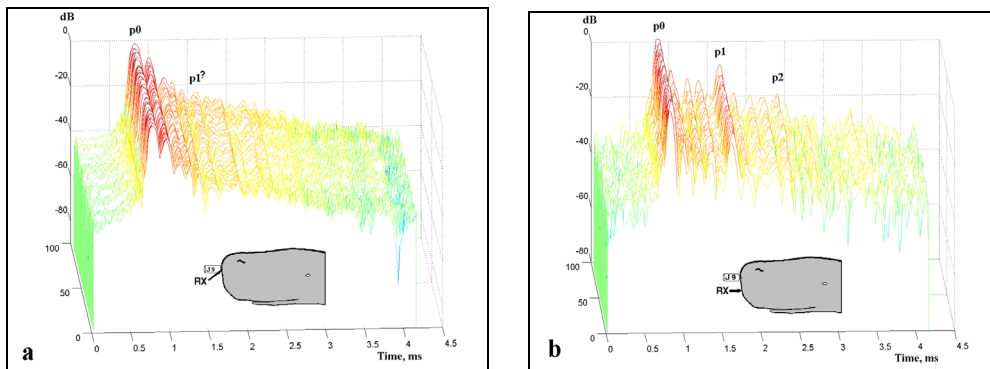

Figure 3. Stimulation at distal sac. **a** is the monostatic case, **b** is the bistatic case.

4. Discussion

Before interpreting the data, some limitations of the approach of exciting the putative sound transmission structures in the nose of a sperm whale cadaver will be commented upon. Although post mortem changes in sound transmission properties (due to bubble formation) have indeed been reported (MacKay, 1988), the basic reflection patterns obtained demonstrate acoustic transparency to be present in the immediate *post mortem* period, so whatever changes may have occurred, the fundamental acoustic structure appears to have been intact. More of a concern is that the sound source (J9) is rather big and placed outside the animal, as were the receiving hydrophones. It is not possible to quantify how much of the sound energy was actually projected into the animal and precisely where, nor is it possible to evaluate the effects of having the source operating at some distance from the animal's own source (assumed to be the monkey lips). Changes in the reflection patterns observed over periods of a few seconds

are interpreted as consequences of minor instabilities in position of the handheld transducers, indicating that the detailed geometry is of importance for the reflection patterns. This obviously also applies to the levels recorded by the monostatic receiver.

The acoustical role of the distal sac is another concern. This sac is situated anterior to the monkey lips. Assuming it to be air filled, it should be an efficient reflector of sound and thus preventing sound from the J9 from reaching the monkey lip complex in situations such as Fig. 3, or the receiving hydrophone in situations such as Fig. 2b. The poor pulse return in Fig. 3a may reflect such effects of the distal sac. However, pulses are evidently reaching the distal sac hydrophone in situations such as Fig. 2a. Thus, the assumption about an air-filled, sound blocking sac was not supported. At the same time, it is hard to explain the observation of p2 pulses without involving reflective properties of this sac. Possibly, if the sac has some air but is partially collapsed, transmission and reflection might occur at the same time but at different areas across the sac. During the necropsy, water was not found in the distal sac. The living animal most likely can control this sac such that it can be empty of air, or partially or completely filled. Reflections from the surroundings were either too early (possible surface reflections) or too late (pool side reflections) to interfere with the air sac reflections, but may contribute to the minor peaks. The advantages of using a biomimetic signal and mimicking an adult sperm whale pulse for excitation are debatable. A frequency modulated sweep, as used by Møhl (2001), appears to be less sensitive to constructive and deconstructive interferences and injected more energy than the single-period click used in this experiment. The consistent picture is, however, that a reflection (p1) occurring after about 0.8 ms, is present in all recordings. It may not be readily detectable in both tracks of a given recording, since the record from the monostatic hydrophone at the transmitter may be masked (see Fig. 3a).

Also, a variation of $\pm$ 0.05 ms in this delay is seen from series to series, but not within a given series. There may be several components in this variation. However, it has only a minor influence in predicting the distance between the two major candidates for sound reflectors, the distal and the frontal sac. The predicted range is from 52 to 61 cm. The physical distance found during dissection (55 cm) is within this range. The interpretation of the p1-pulse being a reflection of the frontal sac is thus quantitatively consistent with this observation. That the physical length of the spermaceti complex can be predicted by acoustical methods supports the basic concept of the theory of sound generation in the sperm whale as first presented by Norris and Harvey (1972). That such predictions are reasonably and equally accurate in the two cadaver experiments on the 3.1 m neonate of the present study and the 15.1 m male in the Møhl (2001) study is further reassuring. The importance of the acoustic function of the spermaceti complex to the biology of this species is indicated by the presence of its basic properties in a neonate. It is noted that the p1-pulse can be observed irrespective of where (distal sac or junk) sound is injected and where it is recorded. Accepting the interpretation that this pulse derives from the first reflection at the frontal sac, this experimental result shows that the spermaceti case and the junk are indeed an acoustical continuum. The same conclusion was reached only by inference in the Møhl (2001) study, in which the bistatic configuration was not used. An anatomical connection between the spermaceti compartment and the junk is described by Cranford (1999). The combined evidence thus suggests a bent horn analogy, as in a bassoon: sound is channeled rearwards in the spermaceti case from the monkey lips back toward the frontal sac and there reflected forward through the junk. Pulses traversing the spermaceti complex several times (see Fig. 1 and Fig. 2b) are not often seen in the present material. Recalling the multi-peak returns as seen in Figs. 2 and 3, it may be hazardous to assign specific pulse numbers beyond p1. It is consistently found that the p0 – p1 interval is slightly larger (about 50 μs) than the p1- p2 interval, indicating a shorter transmission path for p2 pulses. This delay may represent transmission time across the distal sac and its anterior side.

Finally, the multitude of peaks between the p0, p1,..pn -series is evidence for multiple paths of the sound under the present, experimental conditions. With the source away from its natural position (the monkey lips) this may not be surprising. Also, the proximity of the water surface is a confounding factor. It is noted, however, that 'out-of-order' pulses have been seen, both in off-axis recordings from the field (Møhl et al., 2000, Fig. 1), and in the previous transmission study (Møhl, 2001). Thus, the sperm whale nose may have modes of transmission additional to the one described by the Norris and Harvey (1972) scheme. That the cross-section of the inferred acoustic tube (the bent horn formed by the spermaceti case, the frontal sac reflector, and the junk) is not small relative to the wavelength is a condition for such additional modes. To illuminate this and similar questions on the intranasal sound transmission in sperm whales, experiments with transducers inside the spermaceti complex and the junk appear to be the next, logical step.

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