Acoustic radiation from the head of echolocating harbor porpoises
(Phocoena phocoena)

Whitlow W. L. Au1,*, Ronald A. Kastelein2, Kelly J. Benoit-Bird3, Ted W. Cranford4 and Megan F. McKenna4

1Marine Mammal Research Program, Hawaii Institute of Marine Biology, P.O. Box 1106, Kailua, HI 96734, USA, 2Sea Mammal Research Co., Harderwijk, The Netherlands, 3College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, OR 97331-5503, USA and 4Biology Department, San Diego State University, San Diego, CA 92182, USA

*Author for correspondence (e-mail: wau@hawaii.edu)

Accepted 3 May 2006

Summary

An experiment was conducted to investigate the sound pressure patterns on the melon of odontocetes by using four broadband hydrophones embedded in suction cups to measure echolocation signals on the surface of the forehead of two harbor porpoises (Phocoena phocoena). It has long been hypothesized that the special lipids found in the melon of odontocetes, and not in any other mammals, focus sounds produced in the nasal region that then propagate through the melon, producing a beam that is directional in both the horizontal and vertical planes. The results of our measurements supported the melon-focusing hypothesis, with the maximum click amplitude, representing the axis of the echolocation beam, located approximately 5.6–6.1 cm from the edge of the animal’s upper lip along the midline of the melon. The focusing is not sharp but is sufficient to produce a transmission beam of about 16°. Click amplitude dropped off rapidly at locations away from the location of site of maximum amplitude. Based on comparisons of forehead anatomy from similar sized porpoises, the beam axis coincided with a pathway extending from the phonic lips through the axis of the low-density/low sound velocity lipid core of the melon. The significant interaction between click number and hydrophone position suggests that the echolocation signals can take slightly different pathways through the melon, probably as a result of how the signals are launched by the production mechanism and the position of the acoustically reflective air sacs.

Key words: harbor porpoise, Phocoena phocoena, echolocation signals, sound pressure level, melon, lipid, contact hydrophone.

Introduction

The first experimental evidence of sounds produced pneumatically with air being pushed past pairs of internal phonic lips within the nasal system of dolphins has recently been obtained by simultaneous high-speed video endoscopy and acoustic monitoring (Cranford, 2000). In the harbor porpoise (Phocoena phocoena), a low density path connects the phonic lips (formerly referred to as the MLDB or monkey lips/dorsal bursae complex) to the posterior portion of the melon to couple sounds into the melon and eventually into the water (Cranford, 1988; Cranford et al., 1996). Varanasi and Malin were among the first to study the chemical composition of the melon lipid (Varanasi and Malin, 1971); they found that it was composed mainly of triacylglycerol and wax esters. Since then, a number of studies have been performed on the chemical, acoustical and mechanical properties of melon lipids for a variety of odontocete species (Blomberg, 1974; Litchfield et al., 1971; Litchfield et al., 1979; Litchfield et al., 1973; Varanasi et al., 1975; Varanasi and Malin, 1972; Varanasi et al., 1983). The topography of lipid fractions is thought to be at the functional apex of the refractive process in the beam formation (Norris, 1968). The air sacs and the upper jaw play a role in directing sounds towards the melon and refraction of the sounds propagating in the melon shape the beam that emerges from the animal’s forehead (Aroyan et al., 1992). These lipids are also found in the lower jaws of odontocetes and probably function to focus the received sound beam (Norris, 1968; Aroyan, 2001). Sound velocity measurements of tissue samples from a dolphin melon indicated a graded sound velocity profile, with a low velocity core near the midline of the melon and increasing velocity outwards toward the surface of the melon (Litchfield et al., 1973; Norris and Harvey, 1974). A low-density core that likely corresponds to the low-velocity pathway through the melon has been shown in X-ray computer tomography (CT) scans (Cranford, 1988; Cranford et al., 1996). Sounds propagating in an inhomogenous sound
velocity structure will be governed by Snell’s law so that as sound propagates through a medium of changing sound velocity, the sound will refract or bend towards the lower velocity region (Urick, 1983). In the dolphin’s melon, the refraction should be towards the low-velocity core, causing sounds to be focused and projected in a beam that is directional in both the vertical and horizontal planes (Au et al., 1999). The focusing is not sharp but is sufficient to produce a transmission beam that is approximately 16° in both the horizontal and vertical planes.

A numerical simulation of sound propagation through a modeled melon of a common dolphin (Delphinus delphis) numerically solved the two-dimensional inhomogenous wave equation using a finite difference technique (Aroyan et al., 1992). The density structure of the animal’s head was obtained from a CT scan in the parasagittal plane, from which the corresponding velocity structure was estimated. Aroyan et al. showed that the melon structure, along with the different air sacs and the skull, all played a part in focusing the sound propagating from the nasal region of the animal through the melon into the water. However, the elevation angle of the resulting beam matched closely the elevation angle measured with a live bottlenose dolphin only when the source was assumed to be in the vicinity of the phonic lips and the melon was included in the numerical simulation (Au et al., 1986). Elegant as this simulation study was (Aroyan et al., 1992), the study was theoretical and certain assumptions were made on the relationship between the sound velocity and density of tissues in the head of the Delphinus. The analysis was also done in a single parasagittal plane making it a two-dimensional problem, but in reality the propagation in the dolphin’s head is a three-dimensional (3D) process and acoustic energy reflected in the other planes could influence the resulting beam. Finally, it was tacitly assumed that the air sacs of the dead dolphin would be the same as a live phonating animal. However, the sound production process is very dynamic (Dormer, 1979), with air being pumped into the various sacs causing the shape and volume to be continuously modified, making it extremely difficult to simulate.

The purpose of this study was to obtain empirical data on the pattern of acoustic emissions from the porpoise head, and to consider how the melon or other structures in the head might affect the click emission pattern. The empirical data were obtained by measuring the sound field of echolocation signals on the surface of head of two harbor porpoises. Although the echolocation beam pattern of Phocoena phocoena has already been measured (Au et al., 1999), it is difficult to relate those results to the sound field on the head and to determine where the axis of the beam is located on the head of the animal.

**Materials and methods**

**Experimental configuration and approach**

The study was conducted at the Dolphin Rehabilitation and Research Center in the Waterland, Neeltje Jans, The Netherlands, with two male harbor porpoises Phocoena phocoena L., named Daan and Jordy. The porpoises were housed in the same floating net pen, 20 m wide×34 m long, as described previously (Kastelein et al., 1999). During the acoustic measurements the porpoise were kept in two small enclosures (2 m×4 m) on one end of the floating pen structure. Daan was approximately 5 years old, weighing 35 kg and measuring 135 cm in length, whereas Jordy was about 2 years old, weighing 24 kg and measuring 120 cm in length.

Four specially constructed ‘suction cup’ hydrophones were used to measure echolocation signals, a technique first used...
by Diercks et al. (Diercks et al., 1973). Each hydrophone consisted of a cylindrical piezoelectric element similar to the elements used in the Bruel and Kjaer 8103 hydrophones, but enclosed within a suction cup constructed of degassed polyurethane compound (Uralite 3138). Each piezoelectric cylinder was made of PZT (lead zirconate titanate) material with an outer diameter of 6.35 mm, a wall thickness of 1.15 mm and a height of 6.35 mm. The diameter at the base of a suction cup when attached to the porpoise measured 2.8 cm. The hydrophones were attached to the porpoises in the three different configurations shown in Fig. 1. The reference hydrophone, denoted as R, was always placed at the same position for each of the three array configurations. The suction cups were placed on the animal underwater to ensure that air was not trapped in the cups. The position of the hydrophones during each trial was photographed to confirm their positions. A trainer loosely held each porpoise by having her arms extended underneath the animal, which was totally submerged while it scanned its environment with echolocation clicks. A trial was accepted only if all the suction cups remained on the animals throughout the trial. The suction cups were removed after each trial.

The hydrophones were calibrated in a test tank using a sound projector and a calibrated hydrophone for frequencies up to 150 kHz in 10 kHz increments, and in 5 kHz increments for frequencies between 130 and 150 kHz. The average sensitivity for frequencies between 130 and 150 kHz, frequencies typical of *Phocoena* echolocation signals (Au et al., 1999), was $-219$ dB re. 1 µPa for hydrophone-1, $-218$ dB for hydrophone-2, $-217$ dB for hydrophone-3 and $-219$ for hydrophone-4. Accurate hydrophone calibration was necessary since we considered the differences in levels measured by each hydrophone. The response of all the hydrophones dropped off rapidly at a rate of approximately 12 dB per octave beyond 140 kHz so that the hydrophones also functioned as anti-aliasing filters.

Echolocation signals were digitized with two Gage-1210 (Montreal, QC, Canada), 12 bit dual simultaneous sampling data acquisition boards that were connected to a ‘lunch box’ computer via two EISA slots. The data acquisition system operated at a sample rate of 500 kHz with a pre-trigger capability. When the computer signaled the Gage-1210 to collect data, four channels of acoustic signals were simultaneously and continuously digitized with the results going into separate circular memories on each Gage-1210 board. When an echolocation signal was detected by the reference hydrophone, it triggered the data acquisition board. 128 pre-trigger points and 128 post-trigger points were collected for each channel and saved to the computer. A maximum of 100 clicks were collected for each trial and the procedure was continued until a minimum of 300 total clicks were collected for each hydrophone geometry and each animal.

The shape and dimensions along the surface of each animal’s head were measured when the porpoises were removed from the water for their weekly physical examination. The curvature of the head was measured by depressing a flexible shape-retaining ‘French’ curve on different parts of the head and tracing the shape on a sheet of paper. The measurements were used to scale the animals to a CT scan of the same species of a similar size and age. The positions of the hydrophones were mapped on the 3D images in order to correlate the acoustic data with the anatomy.

**Results**

At least three hundred clicks were collected for each animal as the porpoises scanned the surroundings of the net enclosure after the suction cups were attached to them. Typical waveforms of the echolocation clicks detected by the different hydrophones in the line and T1 configuration are shown in Fig. 2. The locations of each hydrophone are indicated by the small circles on the porpoise head. The main component of the waveforms appear to be very similar to those measured in the far field by a number of investigators (Au et al., 1999; Møhl and Andersen, 1973; Wiersma, 1982). However, there were some lower amplitude components following the main pulse (see Fig. 2) that were similar to measurements made in the near-field of a bottlenose dolphin (Au, 1993). The peak frequency for the 300 signals measured by the reference hydrophone in the line configuration was 139.2±3.4 kHz for Daan and 138.6±6.2 kHz for Jordy (means ± s.d.).

The acoustic pressure (means ± s.d.) measured by each hydrophone in the line configuration are shown in Fig. 3A for Daan and in Fig. 3B for Jordy. The piezoelectric sensors were spaced approximately 3.5 cm apart in this configuration. Also shown in each panel of Fig. 3 is the CT scan of a harbor porpoise. The CT scan is from a different animal and its dimensions were scaled to the measurements made on Daan and Jordy during their weekly physical examination. The sound velocity of the lipid within the melon is coded by color, with red being the region of the low density and low sound velocity core. The two dots on the right side of each CT scan represent one pair of phonic lips. A parasagittal CT slice was used so that the presumed sound generation complex containing the phonic lips would be visible, while a mid-sagittal slice would not contain the phonic lips. The differences in the melon structure between a mid-sagittal and parasagittal slice are relatively small when viewed from the locations of the hydrophones (Cranford et al., 1996).

The pattern of the results shown in Fig. 3 for both animals was very similar. A univariate analysis of variance (ANOVA) of the results revealed that hydrophone position had a significant effect on the measured click amplitude. $F_{0.001}$, d.f. = 3, $F = 3935$ for Daan and $F = 3391$ for Jordy. The click number also had a significant effect on the measured click amplitude ($F_{0.001}$, d.f. = 299, $F = 28$ for Daan and $F = 18$ for Jordy). Post-hoc comparisons revealed that for each animal, click amplitude at each hydrophone was significantly different from click amplitude at every other hydrophone (Dunnett’s $C$ test, $P < 0.05$ for all comparisons). The reference hydrophone (hydrophone-2) detected the highest acoustic pressure, while hydrophone-1 detected a slightly lower pressure and both
The reference hydrophone always received the emitted signal before the other hydrophones in the line configuration, for both animals. The relative time between the reception of the signal by the reference hydrophone and the other hydrophones was estimated by determining the cross-correlating function of the signal received by the reference hydrophone and the other hydrophones. If we designate the digitized signal received by the reference hydrophone as $s_2(k)$ and the digitized signal of another hydrophone as $s_i(k)$, where $i$ is the index of the digitized signal and is equal to 1, 2, ..., $n$, and $i$ denotes the specific hydrophone and has values of 1, 3, 4, then the cross-correlation function of the two signals can be expressed as

$$c(j) = \sum_{k=1}^{n} s_2(k)s_i(k+j),$$

where $j$ is the number of samples $s_i$ is being delayed and can have values of 1, 2, ..., $n$. The cross correlation function is determined for a number of $j$ values and the best time estimate of the delay is at the $j$-value at which the correlation function is maximum (Spiesberger and Fristrup, 1990). The results of the time difference measurements are given in Table 1, where $\Delta T_{2-4}$ is the time of arrival difference of the signal at the reference hydrophone 2 and the i-th hydrophone. A one-way ANOVA analysis and post-hoc Tukey test revealed that time differences $\Delta T_{2-4}$ and $\Delta T_{2-3}$ were not statistically different in both animals but $\Delta T_{2-1}$ was significantly different from the other two time differences for both animals ($P<0.05$, d.f.=2, $F=142$ for Daan and $F=14$ for Jordy). The results for both animals show relatively good consistency, with hydrophone-2 receiving the signal first, followed by hydrophone-1 with a delay between 14.5–15.5 µs, and the signals arriving at hydrophones -3 and -4 being delayed between 19.1–21.4 µs.

The results obtained with the T1 and T2 configurations are shown in Fig. 4B. For each array configuration, the mean value of each hydrophone output was referenced to the mean sound pressure level measured by the reference hydrophone. The reference hydrophone measured the highest voltage for each configuration and its level was set to 0 dB. The results of the two configurations were then combined so that a more complete appreciation can be obtained on how sound varied on the head of the porpoises. Fig. 4A shows two CT scans, the top one showing a horizontal slice through the phonic lips and the bottom scan showing a parasagittal slice with the color dots indicating the approximate position of each hydrophone.

A univariate ANOVA test of the results for Daan revealed that hydrophone position had a significant effect on the measured amplitude for both T-configurations ($P<0.001$, d.f.=3, $F=3935$ for T1 and $F=2632$ for T2). Similarly, the click number had a significant effect on the measured amplitude ($P<0.001$, d.f.=299, $F=5$ for T1 and T2). Multiple post-hoc comparisons using a Dunnett’s C test showed that for each configuration, each hydrophone was significantly different.
from every other hydrophone at the \( P<0.05 \) level. The univariate ANOVAs test of Jordy’s data showed a significant effect only for hydrophone position for the T2 configurations \( (P<0.05, \text{d.f.}=3, F>0.05 \text{ for all other comparisons}) \). Multiple post-hoc comparisons with Dunnett’s C tests showed that for the T1 configuration for Jordy, the reference hydrophone was significantly different from hydrophones -3 and -4 but not hydrophone-1 at the \( P<0.05 \) level. No other hydrophone comparisons were significant. For the T2 configuration, the reference hydrophone was significantly different from each of the other hydrophones \( (P<0.05) \) but none of the other hydrophones were significantly different from each other.

There were several instances in the data in which there were changes in the relative amplitudes of the signals with respect to the reference hydrophones that occurred on consecutive clicks. Examples of such changes with the porpoise Daan for three consecutive clicks observed with the line array geometry are shown in Fig. 5 and for the T1 array geometry in Fig. 6. The changes in the relative amplitude of the signals can best be seen by comparing the signals received by hydrophones -1, -3 and -4 with that received by hydrophone-2 (the reference hydrophone). In Fig. 5, the amplitude of the signal detected by hydrophone-1 decreased progressively relative to the signal detected by hydrophone-2 for the three consecutive clicks. In Fig. 6, the amplitude of the first click detected by hydrophones -1 and -2 is almost equal. However, the second click on hydrophone-1 is lower than that of hydrophone-2. The third click on hydrophone-1 is even lower compared to hydrophone-2. Since the hydrophones are fixed in position, the changes in the relative amplitude can only have occurred because of changes in the trajectory that the signals follow to each hydrophone, probably caused by the manner in which the signals were produced and the positional conformation of the air sacs. The interclick intervals were in the 20–40 ms range so that mechanical adjustment of the melon was highly unlikely. Similar examples of changes can be obtained for the porpoise Jordy.

### Table 1. Arrival time difference between the reference hydrophone (hydrophone-2) and the i-th hydrophone

<table>
<thead>
<tr>
<th></th>
<th>Daan</th>
<th>Jordy</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta t_{2,1} ) (( \mu s ))</td>
<td>14.5 \pm 4.0</td>
<td>15.5 \pm 7.6</td>
</tr>
<tr>
<td>( \Delta t_{2,3} ) (( \mu s ))</td>
<td>21.4 \pm 6.3</td>
<td>19.1 \pm 10.8</td>
</tr>
<tr>
<td>( \Delta t_{2,4} ) (( \mu s ))</td>
<td>20.9 \pm 6.2</td>
<td>19.3 \pm 10.2</td>
</tr>
</tbody>
</table>

Values are mean \( \pm \) s.d. \( (N=300) \).

### Discussion and conclusions

The results shown in Fig. 4 indicate the region of maximum acoustic pressure on the surface of a porpoise head. The region of maximum acoustic pressure was consistent between the two animals, and also consistent with the results from the line array shown in Fig. 3. It is also the first demonstration that the region of maximum sound pressure corresponds to the closest approach of the melon’s low-density core to the surface of the head. The difference between the acoustic pressure measured by hydrophones -1 and -2 in Fig. 3 for both animals was similar to the difference between the corresponding hydrophones in the T1 configuration.

The acoustic pressure dropped off rapidly for hydrophone positions away from the region of maximum value higher up the forehead (towards the blowhole), as indicated by the 12 dB reduction in the level detected by hydrophone-3 compared to hydrophone-2 for Daan and 17 dB for Jordy in Fig. 3. This dramatic reduction in the acoustic level may be explained by the presence of a dense connective tissue blanket or theca (Cranford et al., 1996), which surrounds the posterior aspect
of the melon and extends beyond the blowhole anteriorly, creating a megaphone-like funnel that envelops the posterior aspect of the melon and sound generation apparatuses. The dense connective tissue theca provides a significant impedance mismatch that could channel sound forward and shield the hydrophones above that region.

The CT scan image in Fig. 3 show the assumed sound source to be much closer to hydrophones -3 and -4 than both the reference hydrophone and hydrophone-1, yet the reference hydrophone, which was aligned with the low-velocity core of the melon, always received the emitted signal first for both animals, followed by hydrophone-1. This can only happen if the propagation pathways to hydrophones -3 and -4 were much longer than the pathway to the reference hydrophone, suggesting that the signals received by hydrophones -3 and -4 were probably reflected off either an air sac or the top of the upper jaw or both, and the signals received by the hydrophones -1 and -2 travel in a more direct manner through the head of the porpoises. Unfortunately, the signals received by hydrophones -3 and 4 were attenuated, making it difficult to unequivocally determine if the signals are phase inverted as they should be if they reflected off an air sac. The reason for the apparent absence of a direct pathway from the source to hydrophones -3 and -4 is unclear but may be related to the previously mentioned dense theca of connective tissue surrounding the posterior portion of the melon. The 256 μs of pre-trigger points based on the channel monitoring the reference hydrophone would allow for the acquisition of any direct signals from the region of the sound generator to hydrophones -3 and -4. It is beyond the scope of this study to examine the different pathways that the signals travel through the head of the porpoises. Such an examination of pathways would probably require a CT scan, preferably of a

![CT scan image](image)

Fig. 4. The results from the combined T1 and T2 configurations for both porpoises. (A) The approximate positions of the sensor are overlayed on the CT scans with the color of the sensor corresponding to the acoustic results (B) for each animal. Other details as in Fig. 3.

![Amplitude changes](image)

Fig. 5. (A–C) Examples of changes in the relative amplitudes of the signals in the line array configuration over three consecutive clicks.
live porpoise, and some sort of numerical simulation of the sounds propagating in the porpoise head as was done for the common dolphin (Aroyan et al., 1992). Suffice it to state here that the time of arrival difference results suggest that acoustic propagation within the head of a porpoise is complex and not well understood.

The results in Fig. 4, along with the time of arrival data, suggest that sounds propagating through the melon of the porpoises are being channeled by the melon and that the region of maximum acoustic pressure on the surface of the porpoise head approximately coincides to a low density path from the phonic lips through the center of the melon to the surface of the head.

The averaged peak-to-peak acoustic pressure measured by the reference hydrophone was 4 dB greater for Daan than for Jordy. Daan consistently emitted higher amplitude signals than Jordy. Daan was longer (135 cm versus 120 cm) and heavier than Jordy (34 kg versus 25 kg), suggesting a significant effect of animal size and weight on click amplitude. It is reasonable to speculate that higher amplitudes may have been related to the ability to recruit greater muscle mass by the larger animal to generate signals. The variation in the acoustic pressure may also reflect natural variability in the sound production mechanism.

It should be emphasized that our measurements were in the near-field of the porpoises’ head and therefore the signals will be distorted when compared to what is obtained in the far-field (Au et al., 1978). There are secondary components in the waveforms that are probably the results of reflections of the signal within the head of the animals. Therefore, we resisted any temptation to perform detailed analysis of the frequency characteristics of the signals, except for determining the peak frequency obtained by the reference hydrophone in the line array configuration. The relationship between what is measured in the near-field to what is radiated into the far field is a subject that has not received much attention.

One of the difficulties in measuring echolocation signals in free-ranging dolphins and porpoises is the uncertainty whether or not changes in either the shape or amplitude of the received signals are caused by changes in the orientation of the animal with respect to the hydrophone. In our situation, the suction cups were stationary so that any variations in the relative amplitude of the signals probably occurred within the animals. Using two simultaneous high-speed video endoscopic recordings, Cranford observed that clicks were produced in Tursiops truncatus by pushing air across the phonic lips, setting the associated tissue complex into vibration (Cranford, 2000). In some situations, the right phonic lips were vibrating with the left being relatively quiescent while in other situations, the left phonic lips were vibrating with the right remained motionless. There were also occasions in which pulses of air actuated both the left and right phonic lips. In each of these situations, the clicks would propagate through the head along different trajectories. Furthermore, air has been observed to pass through different portions of a pair of phonic lips while the animal produced a single click train. Unfortunately, the results of this study alone are inadequate to suggest the most probable cause of the variations in the relative amplitude of the echolocation signals.

Our measurements have provided empirical confirmation of the melon focusing hypothesis proposed by Norris and coworkers (Norris, 1968; Norris and Harvey, 1974). The foreheads of the porpoises in this study, as with all odontocetes, were very smooth with few clear and useable landmarks. Therefore, our hydrophone placements could only be within about ±0.5 cm accuracy. Furthermore, the diameter of the suction cups did not allow for any two adjacent elements to be nearer than about 2.8 cm. While other structures in the head of odontocetes including the skull and air sacs play a role in the formation of the sonar beam (Aroyan et al., 1992; Goodson et al., 2003), our results indicate the important role of the melon and the connective tissue theca in channeling the sound as it exits the head of a porpoise, forming a directional echolocation beam.

---

**Fig. 6.** (A–C) Examples of changes in the relative amplitude of the signals in the T1 array configuration over three consecutive clicks.
We have determined the general location where sound exits the head and have also shown that echolocation signals can propagate along slightly different trajectories within the head, probably because of the manner in which the signals are produced. Therefore, the transmission beam pattern will also vary on a click-to-click basis if the signal trajectory varies. This study has provided the first data to suggest that the porpoise can make fine adjustments to the transmission beam by manipulating the manner in which the signals are produced and propagated through the head.

This work was supported in part by the Netherlands North Sea Directorate (Dr Wanda Zevenboom) and was performed under the authorization of the Netherlands Ministry of Agriculture, Nature Management and Fisheries and by the Office of Naval Research, Dr Robert Gisiner, Program Manager. This was also partially funded by a grant from the National Oceanic and Atmospheric Administration, Project R/FM-7, which is sponsored by the University of Hawaii Sea Grant College Program, SOEST, under the institutional Grant No. NA16RG2254 from NOAA Office of Sea Grant, Department of Commerce. The views expressed herein are those of the authors and do not necessarily reflect the views of NOAA or any of its subagencies. UNHI-SEAGRANT-JC-03-01. Finally, we thank trainer Marjolijn Eisenburg for her assistance in collecting data in the field and Michiel Schotten for his suggestions concerning the manuscript. This is HIMB contribution 1228.

References


