W-Shaped Auditory Threshold Curves of Masu Salmon

Oncorhynchus masou

Takahito Kojima,*1 Tetsuya Shimamura,*1 Kazumasa Yoza,*1 Naoto Okumoto,*2,4 Yoshimi Hatakeyama,*3 and Hideo Soeda*1

(Received March 2, 1992)

We made experiments to measure the auditory threshold of masu salmon Oncorhynchus masou using conditioning with electric shock, and also to determine the resonance frequency of masu salmon and rainbow trout Oncorhynchus mykiss swim bladders. Then we examined the role of the swim bladder as a sound pressure amplifier and transducer.

The auditory threshold curve for masu salmon was W-shaped, with higher thresholds at 300 and 500 Hz in the range of 100-700 Hz. Masu salmon were less sensitive to sounds of 300-500 Hz than to adjacent frequencies. Swim bladders of rainbow trout fully vibrated in the range 300-600 Hz, with resonance frequencies around 400 Hz. On the other hand, masu salmon’s resonance frequencies were not evident. Therefore, the auditory thresholds of masu salmon at 300-500 Hz were high because the swim bladders did not vibrate or transduce the sound to the inner ear at that range. It was assumed that the hearing capabilities were influenced by the characteristics of the swim bladder vibration.

It is known that fish hear a wide frequency range of sound using both the lateral line and the inner ear,1) and that the swim bladder is important as an acoustic pressure transducer to the inner ear.2) Generally, salmonid fish are reported to have poor hearing ability because the swim bladder plays no part in the hearing.3) However, in earlier studies the swim bladder of salmonid fish were not fully inflated.

We measured the auditory threshold of masu salmon Oncorhynchus masou using classical conditioning in which electric shock was employed to change cardiac rhythm after a sound impulse. We also, determined the resonance frequency of masu salmon and rainbow trout Oncorhynchus mykiss swim bladders and examined the role of the swim bladder as a sound pressure amplifier and transducer.

Materials and Methods

The fish for the auditory threshold experiments were 2-year old masu salmon from the National Research Institute of Aquaculture, Nikko Branch. The eighty fish used were 21.1±1.7 (mean±s. d.) cm in fork length and 105.9±23.2 (mean±s. d.) g in body weight. Figure 1 is a diagram of the experimental apparatus. Four shock absorbers were placed under the experimental glass water tank (30×35×60 cm) to dampen floor vibrations. Before each experiment, background noise spectra at the position occupied by the fish were measured with a hydrophone (Oki Electric Industry Co., Type ST1101), an underwater sound level meter (Oki Electric Industry Co., Type SW-1007), and an FFT analyzer (Matsushita Electric Industrial Co., Type VS-3310 A). The sound was emitted from two air speakers placed 30 cm from the side walls of the water tank. Sound impulses lasting 1 s at each frequency and sound pressure range were used.

---

*1 College of Agriculture and Veterinary Medicine, Nihon University, Setagaya, Tokyo 154, Japan (小島隆浩，鈴村啓幸，余進雄：日本大學畜牛建築部).
*3 National Research Institute of Fisheries Engineering, Kachidoki, Chuo, Tokyo 104, Japan (前山良之：水産工学研究所).
*4 Present address: Japan Fisheries Resource Conservation Association, Toyomi, Chuo, Tokyo 104, Japan (現住所：日本水産資源保護協会).
The auditory threshold was controlled by a Wide-function Synthesizer (NF Electronic Instruments Co., Type 1930), an attenuator (Ando Denki Co., Type AL-255), and an amplifier (Matsushita Electric Industrial Co., Type SU-V60).

Before each experiment, a fish was anesthetized with MS-222 diluted to one part in 25,000. After the anesthetic effect was confirmed electrodes (a pair of vinyl coated wires partially peeled to improve electrical conduction) were inserted into the ventral musculature near the heart. After the insertion of the electrodes, the fish was rested in running water for 2 hours or more to allow it to recover from the anesthetic. The experimental fish was set in a plastic net cage at the center of the tank. The electrocardiogram (ECG) was recorded with an electrocardiograph (Fukuda Denshi Co., Type MIC 680) and heart beat intervals were measured.

Conditioning was performed in accordance with the methods of Ishioka et al.4 An electric shock (0.1 s, 20 V DC) was given to the fish just after each frequency signal sound (1 s, 140 dB) (Fig. 2). The sound and electric shock to the fish were repeated 7 times at 5 minute intervals. After conditioning, the fish was rested for more than 12 h before measuring auditory thresholds. Because the heart beat intervals are affected by ambient temperature, water temperature was maintained at 10 to 12°C.

To determine the auditory threshold, the value (mean ± 1.96 × s. d.) of 20 interbeat intervals prior to the sound projection was used as the control reference; a greater interbeat interval than this reference was then accepted as a positive response. Sound pressure was raised progressive-
ly by 2 dB steps and the response was judged to be positive or negative. Auditory threshold was defined as the median sound pressure between that causing a continuous positive response and that causing a negative response. Frequencies in this experiment were 50, 100, 200, 300, 500, 700, 1000, and 1500 Hz. Ten fish were used at each frequency.

We also examined the characteristics of swim bladder vibration relative to the sound frequency at 200 to 800 Hz. Five masu salmon and five rainbow trout were used in this experiment. The masu salmon were 19.3 ± 0.5 g, and the rainbow trout were 21.5 ± 1.1 (mean ± s. d.) g in body weight. A hydrophone was set at a depth of 15 cm in the water tank, and the fish in the net cage was immersed beside the hydrophone. Then the sound was emitted from the two air speakers. We measured hydrophone voltages in 10 Hz increments, when the fish was present (V2) or absent (V1) in the net cage, on both sides of the hydrophone. Averaging the paired values, we calculated the acoustical resonance of swim bladders as $20 \log_{10} \left(\frac{V2}{V1}\right)$ (dB). Water temperature was 8.9 to 12.0°C.

- Fig. 3. Relationship between relative spectrum and sound frequency when emitting 130 dB sound (0 dB re 1 µ Pa) from air speakers for 50, 100, 200, 300, 500, 700, 1000, and 1500 Hz. 0 dB in relative spectrum is equal to 130 dB in sound pressure.
Results

Auditory Thresholds

The efficiency of sound propagation through water and the wall of tank varied with the frequency. The spectral analysis of the signal sound, adjusted to 130 dB at the center of the water tank, was completed for 8 tests (in the frequency range 50–1500 Hz) (Fig. 3). In every case, the 50 Hz component surpassed other frequencies because of the background (“hum”) noise. It was a large component of the sound energy in each test, except the 50, 100 and 200 Hz tests. However, because each signal sound surpassed the other frequency components, the fish was considered to sense the signal sound.

The auditory threshold curve for masu salmon was W-shaped (Fig. 4). At 100 Hz and 700 Hz, the measured thresholds were scattered, and at other frequencies, the variation was relatively small. The solid line connecting the mean values showed the responses to sounds in the 100–700 Hz range. The thresholds at 300 Hz and 500 Hz were higher than at adjacent frequencies. Sound propagation at 300 and 500 Hz was no less effective than at 200 and 700 Hz (Fig. 3).

There were significant differences by t-test between the mean values at 200 and 300 Hz or 500 and 700 Hz at the 5% level in a one-tailed test. It is apparent that the fish were less sensitive to sounds of 300–500 Hz than to adjacent frequencies in the range of 100–700 Hz.

The critical ratio (dB) (the ratio by which the noise spectrum level starts masking the auditory threshold) was evaluated about 20 dB. At 100 and 200 Hz, the differences between the auditory thresholds and noise spectra were less than 20 dB. The 100–200 Hz thresholds were probably affected by background noise, but the other frequency thresholds were not affected.

Characteristics of Swim Bladder Vibration

Resonance of swim bladders of masu salmon and rainbow trout expressed by 20\log_{10} (V_2/V_1) (dB) for 200–800 Hz were shown in Fig. 5, where the symbols of x were the measured values and the smooth curve is calculated as a moving average of seven terms.

Swim bladder responses of masu salmon varied with each individual. Resonance frequencies were not evident, and the values of 20\log_{10} (V_2/V_1) were all low (less than 5 dB). Swim bladders of rainbow trout fully vibrated in the range 300–600 Hz, with resonance frequencies around 400 Hz. It was clear that characteristics of swim bladder vibration of masu salmon resulted in less efficient sound transfer to the inner ear than in rainbow trout and other fish.

Discussion

Masu salmon are less sensitive to sound because the swim bladder is inefficient as an acoustic pressure transducer to the inner ear. In the same manner as Atlantic salmon *Salmo salar* with very little gas in their swim bladder and dab *Limanda limanda* with degenerated swim bladders, they have higher auditory thresholds or narrower auditory ranges than cod *Gadus morhua* or catfish *Ameiurus nebulosus*. Kleerekoper and Rogenkamp, Sand and Hawkins, Chapman and Sand, and Sand and Enger examined the influence of the swim bladder on the hearing capabilities of catfish, cod, dab, and plaice *Pleuronectes platessa*, showing that the auditory thresholds were variable whether or not the fish possessed gas-filled swim bladders.

Masu salmon have a W-shaped audiogram because of the low sensitivity at 300–500 Hz in
the sensitive range of 100–700 Hz. This contrasts with the V-shaped audiogram of rainbow trout and greatest sensitivity at 300 Hz reported by Yamakawa et al.* Swim bladders of rainbow trout are resonant at around 400 Hz, and they almost coincide with the low 300 Hz threshold. Cod with their sensitive hearing have swim bladders resonant around 500 Hz, with vibration characteristics similar to those of rainbow trout.\footnote{M. Yamakawa, F. Iketani, and Y. Hatakeyama: Abstracts of papers in the spring meeting of Jap. Soc. Sci. Fish., 1986, p. 28.}

Masu salmon's W-shaped audiogram and their hearing capabilities are influenced by the characteristics of the swim bladder vibration. The auditory thresholds at 300–500 Hz are high because the swim bladders do not vibrate and do not transduce the sound to the inner ear at the range of 300–500 Hz. Because swim bladders of masu salmon vibrate moderately at higher frequencies, it is thought that they can hear up to

around 700 Hz. Because of weak swim bladder vibration at 200 Hz, masu salmon hear sound at 200 Hz and lower frequencies through the lateral line. Therefore, the range of 200–300 Hz seems to be a boundary range of proper use between the lateral line and the inner ear to hear wide frequency ranges. Furthermore, the threshold value at 200 Hz is lower (more sensitive) than that at 700 Hz, thus the auditory capability of the lateral line appears to be more sensitive than the inner ear. From these results, it is assumed that the sensitive frequency range varies depending on the swimming depths, especially for fish in which buoyancy is regulated by swim bladder inflation. It is significant, therefore, to use mixed or pure tones which cover a wide frequency range in Marine Ranching in which fish schools in a large water body are controlled by sound.

Acknowledgments

The authors are grateful to Dr. Bruce L. Wing and Dr. Stanley D. Rice, U.S. National Marine Fisheries Service, Auke Bay Laboratory, for their critical reading of the manuscript and valuable advice. We also thank former Director Tamezo Maruyama and the staff of the National Research Institute of Aquaculture, Nikko Branch, for their helpful cooperation in our study. Thanks are also due to former students of Nihon University, Messrs Tsutomu Daikoku, Tadashi Tsukayama, Fumitaka Asada, Hitoshi Inoue and Eiji Yasaka for their helpful assistance.

References