OTSUCHI MARINE SCIENCE 27: 1–6 (2002)

Analysis of tunas behavior using acoustic, archival and pop-up tags: A review

Takashi Kitagawa[1]*, Hideaki Nakata[2], Shingo Kimura[1], Takashige Sugimoto[1] and Harumi Yamada[3]

[1] *Ocean Research Institute, University of Tokyo, Nakano, Tokyo 164–8639, Japan*
[2] *Faculty of Fisheries, Nagasaki University, Nagasaki 852–8521, Japan*
[3] *National Research Institute of Far Seas Fisheries, Fisheries Research Agency,*
Shimizu, Shizuoka 424–8633, Japan
**E-mail*: Kitagawa: *takashik@ori.u-tokyo.ac.jp*
Nakata: *nakata@net.nagasaki-u.ac.jp*
Kimura: *kimuras@ori.u-tokyo.ac.jp*
Sugimoto: *sugimoto@ori.u-tokyo.ac.jp*
Yamada: *hyamada@fra.affrc.go.jp*

Tunas of the genera *Thunnus* and *Katsuwonus* are important fishery resources in the neritic regions of Japan. Although a large amount of information about tunas behavior has been collected, it is very fragmentary and very unquantitative because the data are based on empirical fishing information. Recent technological developments in acoustic transmitters, archival tags and pop-up tags have made it possible to simultaneously monitor swimming behavior of various species of animals, ambient physical and internal physiological information as digital data. However, the duration of successful tracks of tunas using acoustic tags has been restricted to about one week owing to the difficulty of tracking for long periods in rough seas, and results in researchers' fatigue and consequent loss of the target. In the last few years, technological advances in archival and pop-up tags have been achieved, which enable researchers to record time-series data of longer duration and higher resolution compared to previous acoustic studies. Thus, it will be possible to elucidate a seasonal change and developmental processes of tuna behavior. In addition, since the tags detect feeding events of tunas, it will be possible to comprehensively understand relationship between fish behavior and physical biological environment. Moreover, if technological developments of geolocation progress, three-dimensional behavior of fish can be expected.

Key words: tuna, behavior of tuna, acoustic transmitter, archival tag, pop-up tag

INTRODUCTION

Tunas genus *Thunnus* (including yellowfin, albacore, bigeye, blackfin, longtail, southern bluefin and Atlantic and Pacific bluefin tuna) and *Katsuwonus* (skipjack tuna) are one of the most important fishery resources in the neritic region of Japan. Significantly large amounts of biological information (age and growth, reproduction, distribution, etc.) have been collected for analysis of population dynamics and fisheries management of the tunas (e.g. Sund et al. 1981). This information is very fragmentary and unquantitative, because it is often inferred from fisheries data. In addition, various studies have attempted to delineate the habitat requirements of tuna species from employing relationships between catch statistics and oceanographic conditions averaged over time and space (Blackburn and Williams 1975), but the averaged catch statistics and environmental data do not necessarily elucidate these relationships. This is because this data usually were not gathered simultaneously and (as demonstrated by Sharp and Francis 1976) error terms caused by averaging are usually too broad to show meaningful relationships (Brill 1994). Therefore, it is very important to collect more detailed scientific information on the distribution and movement of tunas, as well as detailed relationships between their habitat and oceanographic conditions.

Recently technological advances in acoustic transmitters have been realized. Hunter et al. (1986) reviewed behavioral study of tunas using acoustic tags from the 1970s to the early 80s, and Koido and Miyabe (1990) and Miyabe and Okamoto (1998) reviewed the studies up to the early 90s. Most recently technologies in archival and pop-up tags have made it possible to monitor the swimming behavior of various species of animals including external physical and internal physiological information, simultaneously. In this paper, studies on the behavior of tunas archival and pop-up tags are described in addition to behavioral studies using acoustic transmitters. Moreover, benefit of archival and pop-up tags for investigating tunas' behavioral ecology is also discussed.

STUDIES OF TUNAS BEHAVIORS USING ACOUSTIC TRANSMITTERS

An acoustic (ultrasonic) tracking system consists of a transmitter attached to the fish, and a directional hydrophone and receiver system installed on a tracking vessel. Since pressure and temperature sensors are installed in the transmitters, swimming depth of fish and ambient water temperature data are transmitted to the receiver system on board. Fish geolocation is also measured via GPS on the vessel.

Summary of acoustic tracking of tunas is shown in Table 1. The first success of tracks of tuna using the acoustic system was conducted by Yuen (1970), who tracked 2 small skipjack tuna (*Katsuwonus pelamis*) to obtain information on their behavior associated with movement of water mass-

Table 1. Summary of tuna acoustic tracking.

	Tuna species	Body weight or fork length	Sample size	Track duration	Type of data recorded
Carey and Lowson (1973)	Atlantic bluefin	230–270 kg	7	6–56 hrs	water temp., internal temp.
Lutcaveage et al. (2000)	Atlantic bluefin	136–340 kg	11	3.5–48 hrs	depth, geolocation
Marcinek et al. (2001)	Pacific bluefin	81–119 cm	6	9–68 hrs	depth, internal temp., geolocation
Laurs et al. (1977)	Albacore	84–87 cm	3	28–50 hrs	geolocation
Holland et al. (1990)	Bigeye	57–75 cm	4	10–30 hrs	depth, geolocation
Koito and Miyabe (1990)	Bigeye	46–55 cm	6	6–76 hrs	depth, geolocation
Holland et al. (1992)	Bigeye	79 cm	2	29 hrs	depth, water temp., internal temp.
Josse et al. (1998)	Bigeye	35–84 cm	2	24 hrs	depth, geolocation
Carey and Olson (1973)	Yellowfin	87–98 cm	4	9–48 hrs	depth, geolocation
Yonemori (1982)	Yellowfin	63–70 cm	4	8–32 hrs	depth, geolocation
Cayré and Chabanne (1986)	Yellowfin	54 cm	1	89 hrs	depth, geolocation
Holland et al. (1990)	Yellowfin	44–75 cm	11	9–48 hrs	depth, geolocation
Koito and Miyabe (1990)	Yellowfin	44–79 cm	4	9–34 hrs	depth, geolocation
Cayré (1991)	Yellowfin	73–105 cm	3	13–24 hrs	depth, water temp., geolocation
Block et al. (1997)	Yellowfin	75–94 cm	3	54–72 hrs	depth, geolocation
Josse et al. (1998)	Yellowfin	60 cm	1	24 hrs	depth, geolocation
Marsac and Cayré (1998)	Yellowfin	49–100 cm	8	11–44 hrs	depth, geolocation
Yuen (1970)	Skipjack	40–44 cm	2	12–161 hrs	geolocation
Dizon et al. (1978)	Skipjack	70 cm	3	10–24 hrs	depth, water temp., geolocation
Bard and Pincock (1982)	Skipjack	44–45 cm	2	3–7 hrs	depth, geolocation
Levenez (1982)	Skipjack	53–55 cm	2	19–44 hrs	water temp., geolocation
Cayré and Chabanne (1986)	Skipjack	57 cm	1	39 hrs	depth, geolocation
Cayré (1991)	Skipjack	41–52 cm	5	3–24 hrs	depth, water temp., geolocation

es off the island of Oahu, Hawaii. A notable feature of these tracks was striking ability of the fish to move away from and return to a precise position every day. Although Dizon et al. (1978), Levenez (1982), Bard and Pincock (1982), Cayré and Chabanne (1986) and Cayré (1991) also tracked a few skipjacks, their tracking durations were very short (at most 44 hours Levenez (1982)).

Regarding yellowfin tuna *T. albacore* and bigeye tuna *T. obesus*, Fish Aggregating Devices (FADs) were developed in the early 80s as 'miracle solutions' for making populations of tunas available to small-scale fisheries of island developing countries (Marsac and Cayré 1998). Yonemori (1982), Cayré and Chabanne (1986), Holland et al. (1990), Koido and Miyabe (1990), Cayré (1991), Josse et al. (1998), and Marsac and Cayré (1998) investigated the movement of yellowfin and bigeye around FADs using acoustic transmitters. In most of the studies, fish remained around FADs, however, in other studies, fish moved away at night and returned to FADs the next morning (Cayré and Chabanne 1986, Holland et al. 1990, Marsac and Cayré 1998). Large adult yellowfin repeatedly re-visit the same FAD, and appear able to navigate precisely between FADs (Brill et al. 1999). Josse et al. (1998) suggested that scattering layers (SSL), assimilated as food, played an important role in vertical and horizontal tuna movements.

Vertical movements of yellowfin tuna in the open ocean were also investigated (Carey & Olson 1982, Block et al. 1997). According to Block et al. (1997), yellowfin is predominantly confined to the surface mixed layer above the thermocline and the fish made periodic short dives below the thermocline, encountering cooler temperatures. Incidentally, this corresponds to the empirical finding that purse seine catches of yellowfin and skipjack are considerably large in the thin mixed layers above sharp thermoclines (Green 1967). Albacore, *T. alalunga*, concentrated in the vicinity of upwelling fronts and moved away when upwelling ceased and the front dispersed (Laurs et al. 1977).

Holland et al. (1990, 1992) measured swimming depth and muscle temperature of bigeye, simultaneously, and found that bigeye spent most daylight hours well below the thermocline (in 15°C water) but made regular, brief, upward excursions into mixed layers. Bigeye reduce the efficacy of their vascular counter-current heat exchangers while gaining heat from the environment, then increase it again when they return to depths below the thermocline, known as 'physiological behavioral thermoregulation' (Holland et al. 1992). According to Dagorn et al. (2000), large bigeye swam within the first 100 m below the surface during the night and at depth between 400 and 500 m during the daytime, making upward excursions approximately every 2.5 h. Further, the fish exhibited clear relationship with the SSL.

Carey and Lawson (1973) were measured ambient water and internal temperature of 230–270 kg Atlantic bluefin *T. thynnus thynnus*. Bluefin made abrupt dives periodically from surface water of 18°C to the thermocline at 4–5°C. In addition, bluefin, which experienced marked changes in water temperature, showed excellent regulation of body temperature (which was, however, pointed out to be an incorrect interpretation by Neill and Stevens (1974), –that is, the body temperature of the bluefin was maintained not by physiological, but by physical means of "their thermal inertia"). Recently, Lutcavage et al. (2000) tracked bluefin (136–340 kg) in the Atlantic and Marcinek et al. (2001) made in the Pacific (11.8–57.6 kg, *T. t. orientlis*). Bluefin spent most of their time in the top of the water column and

Table 2. Summary of studies of tunas behaviors using archival tags or pop-up tags.

	Tuna species	Body weight or fork length	Sample size	Track duration	Type of data recorded	Sampling interval	Type of tag
Gunn et al. (1994)	Southern bluefin	40–50 cm	2	15–33 days	depth, water temp., internal temp., light, geolocation	1–4 min	archival tag
Block et al. (1998)	Atlantic bluefin	96–181 kg	37	3–61 days	water temp., geolocation (only end location of the track)	1 day	pop-up tag
Lutcavage et al. (1999)	Atlantic bluefin	190–263 cm	17	61 days	water temp., geolocation (only end location of the track)	1 day	pop-up tag
Kitagawa et al. (2000)	Pacific bluefin	50–70 cm	15	6–75 days	depth, water temp., internal temp., light, geolocation	128 sec	archival tag
Inagake et al. (2001)	Pacific bluefin	49–55 cm	5	611–1635 days	water temp., geolocation	1 day	archival tag
Marcineck et al. (2001)	Pacific bluefin	127–143 cm	2	24–52 days	depth, water temp., geolocation (only end location of the track)	1 min	pop-up tag
Kitagawa et al. (2001)	Pacific bluefin	50–70 cm	15	6–75 days	depth, water temp., internal temp., light, geolocation	128 sec	archival tag

made occasional dives into deeper and cooler water.

As shown in Table 1, durations of all these successful tracks of tunas using vessels are less than one week. This is due to the difficulty of tracking for long periods in rough seas, and results in researchers' fatigue and consequent loss of the target. Since fish may show abnormal behavior in the first few days after release, a longer monitoring period is essential to estimate their natural behavior, particularly for the investigations of seasonal change and development processes of their behavior.

STUDIES OF TUNAS BEHAVIORS USING ARCHIVAL AND POP-UP TAGS

In recent years, "archival tags" (data storage tags, micro data loggers) have been developed and applied to salmons, plaice, whale shark, cod and tunas (Gunn et al. 1994, 1999, Boehlert 1997, Ogura 1997, Metcalfe and Arnold 1997, Tanaka et al. 1998, 2000, Block et al. 1998a, b, Kasai et al. 1998, 2000, Lutcavage et al. 1999, Naito et al. 2000, Kitagawa et al. 2000, 2001, Walker et al. 2000, Righton et al.2001, Marcinek et at 2001, Inagake et al. 2001, Friedland et al. 2001). The archival tag is an electronic device that measures environmental variables and records raw or processed data in its memory. When an archival tag is attached to an animal, it allows direct examination of the relationship between animal behaviors or physiological conditions and the ambient environment, because the sensor measures the environmental conditions which the animal experiences at that moment. In addition, some versions of archival tags allow rough estimation of fish geolocation every day from time of sunrise and sunset as detected by light sensor (Anonymous 1994, Block et al. 1998b). As for the theory of fish geolocation by light levels, longitudes are estimated the time of sunrise and sunset; Latitudes are estimated by daytime duration (Hill 1994).

These tags enable us to record time-series data for longer durations and higher resolutions when compared to previous tracking studies using acoustic transmitters.

The pop-up tag is attached externally to a fish, releases at a preprogrammed time because of a corrosive linkage, floats to the surface, and then transmits continuously to ARGOS satellites (Block et al. 1998a). Therefore, compared with archival tag, recapture of the animal to access the data is not required. Summary of studies of tunas behaviors using archival tags or pop-up tags is shown in Table 2. Gunn et al. (1994) first applied the archival tag to southern bluefin (*T. maccoyii*). They measured data on depth, body and ambient water temperature of tuna, and clearly detected daily feeding and activity cycles from body temperature changes. Feeding events were indicated by rapid drops of body temperature due to ingesting food or water. These rapid thermal changes could not be explained by a change in ambient water temperature. Further, the fish preferred the upper water column during daylight hours, while at night it routinely swam at depths greater than 30–40 meters (data length 15 days). Regarding Pacific bluefin, Kitagawa et al. (2000) analyzed time-series data on the swimming depth and ambient water temperature recorded every 128 seconds by tags retrieved from 15 fish (data length about 80 days at maximum). In this study, the tags were recovered by fisheries and recovery rate of the tags was 0.143 (15/105). As a result, spatial and seasonal changes of the vertical structure of ambient water temperature were found to have a great influence on the vertical distribution and movement of the bluefin. In addition, Kitagawa et al. (2001) analyzed time-series data on water and peritoneal cavity temperature recorded by tags retrieved from the fish and investigated thermoconservation mechanisms of the bluefin under low ambient temperature. According to their results, the peritoneal cavity temperature of bluefin is maintained when it makes brief and frequent dives to depths through the thermocline. It was further revealed from a heat budget model that thermal inertia or heat production is important for the thermoconservation during the dives. They pointed out that since bluefin cannot maintain body temperature for a long dive, they spend most of their time at the surface and have to avoid rapid temperature change at the thermocline via behavioral thermoregulation. This result is quite different from that of bigeye tuna as reported by Holland et al. (1992). The heat exchangers are disengaged to allow rapid warming as the bigeye ascend from cold water into warmer surface waters, and are reactivated to conserve heat when they return to the depths, which is a process called physiological and behavioural thermoregulation (Holland et al. 1992).

Inagake et al. (2001) described the migration routes of young Pacific bluefin in the western North Pacific in relation to oceanographic conditions. The fish showed clockwise migration patterns closely related with the ocean structure in and around the Kuroshi-Oyashio Inter-frontal Zone. They moved westward in spring in and around the Kuroshio Extension, northward in summer along the warm water intrusions originating from the crest of the Kuroshio Extension, eastward in fall along the south of the Oyashio front, and southward in early winter to the Kuroshio Extension. It is likely that their migration routes are related to changes of chlorophyll-a concentration as well as ocean currents.

Block et al. (1998a, b, 2001), Lutcavage et al. (1999) applied archival tags or pop-up satellite tags to Atlantic bluefin and investigated their temporal and spatial movement patterns in the Atlantic Ocean. Although some authors reported on tag data collected from small sample, they did not necessarily reveal the causal factors affecting the movement of the fish. Advances in technological developments of pop-up tags and increases of sample size retrieved are desirable. Neverthless, according to Lutcavage et al. (1999), the view of bluefin migrating in a region of the mid-Atlantic bounded by Bermuda and the Azores, indicated that spawning size class was primarily found in the Gulf of Mexico in late April-June. Block et al. (1998a) showed that Atlantic bluefin crossed between the western and eastern management zone, indicating that it is necessary to improve the identification of discrete biological stocks. It was also showed that bluefin moved in the Gulf Stream or along the western frontal zone, indicating the blufin prefer warmer water masses to the cooler Labrador Current or coastal water. Marcinek et al. (2001) tracked two Pacific bluefin with pop-up tags in the eastern Pacific and found that these blufin spent the majority of their time in the top parts of the water column in a pattern similar to that observed for yellowfin (Block et al. 1997). According to Block et al (2001), Atlantic bluefin dive to depths of more than 100 m and maintain a warm body temperature. In addition, tagged bluefin make trans-Atlantic migrations and they frequent spawning grounds in the Gulf of Mexico and eastern Mediterranean.

Relationships between vertical distributions of tunas and ambient water temperatures have been described from a viewpoint of fishing ground formation (Suda et al.1969, Uda 1973, Kawai 1980, Koido and Mizuno 1989, Ogawa and Ishida 1989a, b). Since this information, however, was collected only when fishing grounds were formed, the information is very fragmental and lacks generality of tunas behavior. Tracking of tunas with acoustic transmitters were also restricted to no more than a few days duration as described above. In contrast, archival tag provides a fisheries-independent measure of the tunas behavior with environmental and physiological data from the location of tagging. Therefore, if the tags can be retrieved, it will be possible to collect detailed biological information of tunas for longer durations and higher resolutions compared to previous fisheries data analysis or tracking studies.

One of the limits on archival tags is that only physical quantities are measured, suggesting that only the relationship between fish behavior and ambient physical environment such as water temperature, light level, etc can be elucidated. Thus, studies using this tag may fall into the approach of "environment determinism". However, feeding events for tunas indicated by rapid drops of their body temperature, were also detected by the tags (Gunn et al. 1994), suggesting that it is possible to comprehensively understand relationship between fish behavior and the biological environment such as prey, in addition to the physical environment.

CONCLUSION

In this paper, studies on use of acoustic transmitters, archival and pop-up tags in investigations of the behavior of tuna were reviewed. Benefit of archival and pop-up tags for investigating tunas' behavioral ecology was also discussed. Regarding a weak point for technology of archival tags, only once a day can fish geolocations be roughly estimated from the time of sunrise and sunset as detected by the light sensor. In addition, the scale of errors in geolocation estimates from archival tags are considerable (Welch and Eveson 1999). Therefore, for future studies, it is important to increase spatial resolution of the geolocation of the animals or to develop new techniques. These improvements are indispensable for the research on the horizontal migration of pelagic animals. If these technological developments progress, it will be possible to observe 3-dimensional behavior of fish. Moreover if possible, the fish themselves will reveal the nature of their 3-dimensional "real" environment, instead of relying on ship-based measurements.

ACKNOWLEGEMENTS

We are grateful to Y. Uozumi, Z. Suzuki, Y. Ishizuka, S. Tsuji, T. Itoh, and M. Takahashi, National Research Institute of Far Seas Fisheries, and to A. Nitta, Japan NUS Co., for their encouragement. We are also grateful for the advice of M. Arai, of the Otsuchi Marine Research Center. We would like to thank Mr. Sean T. Toczko, Division of Marine Planktology, ORI, Univ. of Tokyo, for correction of English in this text. T. Kitagawa was supported by Research Fellowships of the Japan Society for the Promotion of Science for Young Scientists.

LITERATURE CITED

Anonymous 1994. Archival tags 1994: present and future. NOAA Tech. Memo. NMFS-SEFSC 357: p42.

Bard, F. X. and Pincock, D. 1982. Rapport sur une experience de marquage par microemetteur, de listaos (*Katsuwonus pelamis*) dans le golfe de Guinee, en juillet 1981. ICCAT Col. Vol. Sci. Pap. 17: 184–188.

Blackburn, M. and Williams, F. 1975. Distribution and ecology of skipjack tuna, *Katsuwonus pelamis*, in an offshore area of the eastern trpocal Pacific Ocean. Fish. Bull. U.S. 73: 382–411.

Block, B. A., Keen, J. E., Castillo, B., Dewar, H., Freund, E. V., Marcinek, D. J., Brill, R. W. and Farwell, C. 1997. Environmental preferences of yellowfin tuna (*Thunnus albacares*) at the northern extent of its range. Mar. Biol. 130: 119-132.

Block, B. A., Dewar, H., Farwell, C. and Prince, E. D. 1998a. A new satellite technology for tracking the movement of Atlantic bluefin tuna. Proc. Natl. Acad. Sci. U.S.A 95: 9384–9389.

Block, B. A., Dewar, H., Williams, T., Prince, E. D., Farwell, C. and Fudge, D. 1998b. Archival tagging of Atlantic bluefin tuna

(*Thunnus thynnus thynnus*). Mar. Technol. Soc. J. 32: 37–46.

Block, B. A., Dewar, H., Blackwell, S. B., Williams, T. D., Prince, E. D., Farwell, C. J., Boustany, A., Teo, S. L. H., Seitz, A., Walli, A. and Fudge, D. 2001. Migratory movements, depth preferences, and thermal biology of Atlantic bluefin tuna. Science 293: 1310–1314.

Boehlert, G. W. 1997. Appticaion of acoustic and archival tags to assess estuarine, nearshore, and offshore habitat utilization by salmoids: Introduction and objectvies of the workshop. NOAA Tech. Memo. NMFS-SEFSC 236: 1–6.

Brill, R. W. 1994. A review of temperature and oxygen tolerance studies of tunas pertinent ot fisheries oceanography, movement models and stock assessments. Fish. Oceanogr. 3: 204–216.

Brill, R. W., Block, B. A., Boggs, C. H., Bigelow, K. A., Freund, E. V. and Marcinek, D. J. 1999. Horizontal movements and depth distribution if large adult yellowfin tuna (*Thunus albacares*) near the Hawaiian Islands, recorded using ultrasonic telemetry: implications for the phsiological ecology of pelagic fishes. Mar. Biol. 133: 395–408.

Carey, F. G. and Lawson, K. D. 1971. Temperature regulation in free-swimming blufin tuna. Comp. Biochem. Physiol. 44A: 375–392.

Carey, F. G. and Olson, R. J. 1982. Sonic tracking experiments with tunas. ICCAT Col. Vol. Sci. Pap. 2: 458–466.

Cayré, P. and Chabanne, J. 1986. Marquage acoustique et comportement de thons tropicaux (albacore; *Thunnus albacares*, et listao: *Katsuwonus pelamis*) au voisinage d'un dispositif concentrateur de poissons. Océanogr. Trop. 21: 167–183.

Cayré, P. 1991. Behaviour of yellowfin tuna (*Thunnus albacares*) and skipjack tuna (*Katsuwonus pelamis*) around fish aggregating devices (FADs) in the Comoros Island as a determined by ultrasonic tagging. Aquat. Living. Resour. 4: 1–12.

Dagorn, L., Bach, P. and Josse, E. 2000. Movement patterns of large bigeye tuna (*Thunnus obesus*) in the open ocean, determined using ultrasonic telemetry. Mar. Biol. 136: 361–371.

Dizon, A. E., Brill, R. W. and Yuen, H. S. H. 1978. Correlations between environment, physiology, and activity and the effect on thermoregulation in skipjack tuna. *In* The Physilogical Ecology of Tunas. Sharp G. D. and Dizon A. E. (ed), pp 233–259, Academdic Press, New York.

Friedland, K. D., Walker, R. V., Davis, N. D., Myers, K. W., Boehlert, G. W., Urawa, S. and Ueno, Y. 2001. Open-ocean orientation and return migration routes of chum salmon based on temperature data from data storage tags. Mar. Ecol. Prog. Ser. 216: 235–252.

Green, R. E. 1967. Relationship of the thermocline to success of purse seining for Tuna. Trans. Am. Fish. Soc. 96: 126–130.

Gunn, J. S., Polacheck, T., Davis, T. L. O., Sherlock, M. and Betlehem, A. 1994. The development and use of archival tags for studying the migration, behavior and physiology of southern bluefin tuna, with an assessment of the potential for transfer of the technology to groundfish research. ICES Comm. Meet. (Proc. ICES Symp. Fish Migration) Mini 2.1: 1–23.

Gunn, J. S., Steevens, J. D., Davis, T. L. O. and Norman, B. M. 1999. Observation on the short-term movements and behaviour of whale shanks (*Rhincondon typus*) at Ningaloo Reef, Western Australia. Mar. Biol. 135: 553–559.

Hill, R. D. 1994. Theory of geolocation by light levels. *In* Elephant seals, population ecology, behavior and physiology. B. J. LeBoeuf and R. M. Laws. (ed), pp 227–236, University of California Press, Berkley, California.

Holland, K. H., Brill, R. W. and Chang, R. K. C. 1990. Horizontal and vertical movements of Yellowfin and Bigeye Tuna associated with fish aggregating devices. Fish. Bull. U.S. 88: 493–507.

Holland, K. H., Brill, R. W., Chang, R. K. C., Sibert, J. R. and Fournier, D. A. 1992. Physiological and behavioural thermoregulation in bigeye tuna. Nature 358: 410–412.

Hunter, J. R., Argue, A. W., Bayliff, W. H., Dizon, A. E., Fonteneau, A., Goodman, D. and Seckel, G. R. 1986. The dynamics of tuna movements: an evaluation of past and future research. FAO Fish. Tech. Pap. 277: 1–78.

Inagake, D., Yamada, H., Segawa, K., Okazaki, M., Nitta, A. and Itoh, T. 2001. Migration of young bluefin tuna, *Thunnus orientalis* Temminck et Schlegel, through archival tagging experimets and its relation with oceanofrapic conditon in the Western North Pacific. Bull. Nat. Res. Inst. Far Seas Fish. 38: 53–81.

Josse, E., Bach, P. and Dagorn, L. 1998. Simulataneous observations of tuna movements and their prey by sonic tracking and acoustic surveys. Hydrobiologia 371/372: 61–69.

Kasai, A., Sakamoto, W., Mitsunaga, Y. and Yamamoto, S. 1998. Migration of immature yellowtails *Seriola quinqueradiata*, in the open sea observed by an acoustic transmitter and micro data recording tags. Nippon Suisan Gakkaishi. 64: 197–203.

Kasai, A., Sakamoto, W., Mitsunaga, Y. and Yamamoto, S. 2000. Behaviour of immature yellowtails (*Seriola quinqueradiata*) observed by electronic data-recording tags. Fish. Oceanogr. 9: 259–270.

Kawai, H. 1980. Rings south of the Kuroshio and their possible roles in transport of the intermediate salinity minimum and information of the skipjack and albacore fishing grounds. *In* The Kuroshio IV, Proc 4th CSK Symp Tokyo 1979. pp 250–273, Saikon Publishing Company Limited, Tokyo.

Kitagawa, T., Nakata, H., Kimura, S., Itoh, T., Tsuji, S. and Nitta, A. 2000. Effect of ambient temperature on the vertical distribution and movement of Pacific bluefin tuna (*Thynnus thynnus orientalis*). Mar. Ecol. Prog. Ser. 206: 251–260.

Kitagawa, T., Nakata, H., Kimura, S. and Tsuji, S. 2001. Thermoconservation mechanism inferred from peritoneal cavity temperature recorded in free swimming Pacific bluefin tuna (*Thunnus thynnus orientalis*). Mar. Ecol. Prog. Ser. 220: 253–263.

Koido, T. and Mizuno, K. 1989. Fluctuation of catch for bluefin tuna (*Thunnus thynnus*) by trap nets in Sanriku coast with reference to hydrographic condition. Bull. Japan. Soc. Fish. Oceanogr. 53: 138–152.

Koido, T. and Miyabe, N. 1990. Field observation: tunas. *In* Application of telemetry to aquatic animal behavior. Soeda H. (ed), pp 55–66, Koseisha Koseikaku, Tokyo.

Laurs, R. M., Yuen, H. S. H. and Johnson, J. H. 1977. Small-scale movements of albacore, *Thunnus alalunga*, in relation to ocean features as indicated by ultrasonic tracking and oceanographic sampling. Fish. Bull. U.S. 75: 347–355.

Levenez, J. J. 1982. Note preliminaire sur l'operation Senegalaise de tracking de listao. ICCAT Col. Vol. Sci. Pap. 17: 189–194.

Lutcavage, M. E., Brill, R. W., Skomal, G. B., Chase, B. C., Goldstein, J. L. and Tutein, J. 2000. Tracking adult North Atlantic bluefin tuna (*Thunnus thunnus*) in the northwestern Atlantic using ultrasonic telemetry. Mar. Biol. 137: 347–358.

Lutcavage, M. E., Brill, R. W., Skomal, G. B., Chase, B. C. and Howey, P. W. 1999. Results of pop-up satellite tagging of spawning size class fish in the Gulf of Maine: do North Atlantic bluefin tuna spawn in the mid-Atlantic? Can. J. Fish. aquat. Sci. 56: 173–177.

Marcinek, D. J., Blackwell, S. B., Dewer, H., Freund, E. V., Farwell, C., Dau, D., Seitz, A. C. and Block, B. A. 2001. Depth and muscle temperature of Pacific bluefin tuna examined with acoustic and pop-up satellite archival tag. Mar. Biol. 138: 869–885.

Marsac, F. and Cayré, P. 1998. Telemetry applied to behaviour analysis of yellowfin tuna (*Thunnus albacares*, Bonnaterre, 1788) movements in a network of fish aggregating devices. Hydrobiologia 371/372: 155–171.

Metcalfe, J. D. and Arnold, G. P. 1997. Tracking fish with electric tag. Nature 387: 665–666

Miyabe, N. and H.Okamoto 1998. Case studies by method: Ultra sonic tag (pinger): The 27th Symposioum on Skipjack and tuna fisheries-Research on swimming depth-strata of tuna and other large pelafic fish-. Bull. Japan. Soc. Fish. Oceanogr. 62: 260–263.

Naito, Y., Tanaka, H. and Ueda, H. 2000. Preliminary report of swimming behavior and the response to temperature of lacustrine masu salmon, *Oncorhynchus masou* Brevoort, monitored by data logger during the spawning migration in Lake Toya. Polar Biosci. 13: 87–94.

Neill, W. H. and Stevens, E. D. 1974. Thermal inertia versus thermoregulation in 'warm' turtles and tuna. Science 184: 1008–1010.

Ogawa, Y. and Ishida, T. 1989a. Distinctive features of fluctuations in the catch of *Thunnus thynnus* by set-nets along the Sanriku coast. Bull. Tohoku Reg. Fish. Lab. 51: 11–21.

Ogawa, Y. and Ishida, T. 1989b. Hydrographic conditions governing fluctuations in the catch of *Thunnus thynnus* by set-nets along the Sanriku coast. Bull. Tohoku Reg. Fish. Lab. 51: 22–39.

Ogura, M. 1997. Acoustic and archival tagging work on salmonids in Japan. NOAA Tech. Memo. NMFS-SEFSC 236: 16–27.

Righton, D., Metcalfe, J. and Connolly, P. 2001. Different behaviour of North and Irish Sea cod. Nature 411: 156–156.

Sharp, G. D. and Francis, R. C. 1976. An energetics model for the exploited yellowfin tuna, *Thuunus albacares*, population in the eastern pacfic ocean. Fish. Bull. U.S. 74: 36-51.

Suda, A., Kume, S. and Shiohama, T. 1969. An indicative note on a role of permanent thermocline as a factor controlling the long line fishing ground for bigeye tuna. Bull. Far Seas Fish. Res. Lab. (Shimizu) 1: 99–114.

Sund, P. N., Blackburn, M. and Williams, F. 1981. Tunas and their environment in the Pacific Ocean: a review. Oceangr. Mar. Biol. Ann. Rev. 19: 443–512.

Tanaka, H., Takagi, Y., Iwata, M. and Naito, Y. 1998. The behavior and ambient temperature of homing chum salmon monitored by a data logger. Proc. NIPR Symp. Polar Biol. 11: 62–73.

Tanaka, H., Takagi, Y. and Naito, Y. 2000. Behavioral thermoregulation of chum salmon during homing migration in coastal waters. J. Exp. Biol. 203: 1825–1833.

Uda, M. 1973. Pulsative fluctuation of oceanic fronts in association with the tuna fishing grounds and Fisheries. J. Fac. Mar. Sci. Technol. Tokai Univ. 7: 245–267.

Walker, R. V., Myers, K. W., Davis, N. D., Aysin, K. Y., Friedland, K. D., Corlson, H. R., Boehlert, G. W., Urawa, S., Ueno, Y. and Anma, G. 2000. Diurnal variation in thermal environment experienced by slmonids in the North Pacific as indicated by data storage tags. Fish. Oceanogr. 9: 171–186.

Welch, D. W. and Eveson, J. P. 1999. An assessment of light-based geoposition estimtes from archival tags. Can. J. Fish. aquat. Sci. 56: 1317–1327.

Yonemori, T. 1982. Study of tuna behavior, particularly their swimming depths, by the use of sonic tags. Far Seas Fish. Lab. (Shimizu) Newslet. 44: 1–5.

Yuen, H. S. H. 1970. Behavior of skipjack tuna, *Katsuwonus pelamis*, as determined by tracking with ultrasonic device. J. Fish. Res. Bd. Can. 27: 2071–2079.

総説：超音波ピンガー，アーカイバルタグ、ポップアップ・タグを用いたマグロ類の行動研究

北川　貴士[1]・中田　英昭[2]・木村　伸吾[1]・杉本　隆成[1]・山田　陽巳[3]

[1] 東京大学海洋研究所
〒164–8639　東京都中野区南台1–15–1
[2] 長崎大学水産学部
〒852–8521　長崎市文教町1–14
[3] 独立行政法人水産総合センター　遠洋水産研究所
〒424–8633　静岡県清水市折戸5–7–1

マグロ属 (*Thunnus*)，およびカツオ属 (*Katsuwonus*) 魚類は日本周辺海域で重要な水産資源のひとつとなっている．これまでマグロ類（ここではマグロ属とカツオ属）の行動・遊泳水深に関する情報は数多く集められてきたが，漁獲海域の情報に基づいていたため，断片的で定性的なものであった．近年，超音波ピンガー，アーカイバルタグ，ポップアップ・タグの開発が進み，さまざまな海洋生物の遊泳行動，外部環境，生理状態をデジタルデータとしてモニターできるようになってきた．しかし，超音波ピンガーによる行動観察では，対象魚を見失うことや，荒天退避などにより，数日以上の追跡は困難である．その点アーカイバルタグ，ポップアップ・タグではより長期間にわたって，高精度の時系列データを記録することができる．これにより，マグロ類の行動の季節変化や成長に伴う変化も観察することができるだろう．さらに，データからマグロ類の摂餌に関する情報も検出されるため，その行動と物理学的・生物学的環境との関係を総合的に理解することも可能である．さらに魚の位置情報に関する技術開発が進めば，3次元の行動の観察も可能になるであろう．

Received: 6 August 2001
Accepted: 7 September 2001