

Laboratory and Field Research to Enhance Understanding of Tuna Movements and Distribution, and to Improve Stock Assessment Model

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Test of the feasibility and effects of long-term intramuscular implantation of archival tags in pelagic fishes using scale model tags and captive juvenile yellowfin tuna (*Thunnus albacares*)

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Electronic archival tags capable of measuring and storing (for up to 12 years) data on ambient light level, a fish's depth, and water temperature (from which geographic positions can be estimated) are now commercially available. Although many of the engineering problems have been surmounted, long-term (months to years) tag attachment methods remain problematic for tunas (*Thunnus* spp.) and especially billfishes (*Istiophoridae* and *Xiphiidae*) where large individuals (> 200 kg body mass) can be difficult to restrain or safely remove from the water. Intramuscular placement of archival tags in these fishes could be a desirable method of attachment. We therefore have begun to test the feasibility of long-term intramuscular implantation of archival tags in large pelagic fishes by placing stainless steel scale model tags into juvenile yellowfin tuna (*Thunnus albacares*) held in shore side tanks. We found model archival tags can be easily implanted within the muscle, remain near the body surface as the fish grow, and can be carried for 10 months without causing infection or adverse tissue reactions.

Blood volume, plasma volume, and circulation time in a high energy demand teleost, the yellowfin tuna (*Thunnus albacares*)

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We measured red cell space with ^{51}Cr labeled red blood cells, and dextran space with 500 kDa fluorescein-isothiocyanate labeled dextran (FITC-dextran), in two groups of yellowfin tuna (*Thunnus albacares*). Red cell space was $13.8 \pm 0.7 \text{ ml kg}^{-1}$. Assuming a whole body hematocrit equal to the hematocrit measured at the ventral aortic sampling site and no significant sequestering of ^{51}Cr labeled red blood cells by the spleen, blood volume was $46.7 \pm 2.2 \text{ ml kg}^{-1}$. This is within the range reported for most other teleosts (35-79 ml kg^{-1}), but well below that previously reported for albacore (*Thunnus alalunga*, 83-197 ml kg^{-1}). Plasma volume within the primary circulatory system (i.e. calculated from the ^{51}Cr labeled red blood cell data) was 32.9

$\pm 2.3 \text{ ml kg}^{-1}$. Dextran space was $37.0 \pm 3.7 \text{ ml kg}^{-1}$. Because 500 kDa FITC-dextran appeared to remain within the vascular space, these data imply the volume of the secondary circulatory system of yellowfin tuna is small, and its exact volume not measurable by our methods. Although blood volume is not exceptional, circulation time (blood volume / cardiac output) clearly is less in yellowfin tuna than in other active teleosts. In a 1 kg yellowfin tuna, circulation time is approximately 0.4 min ($47 \text{ ml kg}^{-1} / 115 \text{ ml min}^{-1} \text{ kg}^{-1}$) compared with 1.3 min ($46 \text{ ml kg}^{-1} / 35 \text{ ml min}^{-1} \text{ kg}^{-1}$) in yellowtail (*Seriola quinqueradiata*) and 1.9 min ($35 \text{ ml kg}^{-1} / 18 \text{ ml min}^{-1} \text{ kg}^{-1}$) in rainbow trout (*Oncorhynchus mykiss*). In air-breathing vertebrates, high metabolic rates are necessarily correlated with short circulation times. Our data are the first to imply that a similar relationship occurs in fishes.

Responses of the red blood cells from two high-energy-demand teleosts, yellowfin tuna (*Thunnus albacares*) and skipjack tuna (*Katsuwonus pelamis*), to catecholamines

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In fishes, catecholamines increase red blood cell (rbc) intracellular pH (pH_i) through stimulation of a sodium/proton (Na^+/H^+) antiporter. This response can counteract potential reductions in blood O_2 carrying capacity (due to Bohr and Root effects) when plasma pH (pH_e) and pH_i decrease during hypoxia, hypercapnia, or following exhaustive exercise. Tuna physiology and behavior dictate exceptionally high rates of O_2 delivery to the tissues often under adverse conditions, but especially during recovery from exhaustive exercise when pH_e may be reduced by as much as 0.4 pH units. We hypothesize that blood O_2 transport during periods of metabolic acidosis could be especially critical in tunas and the response of rbc to catecholamines elevated to an extreme. We therefore investigated the *in vitro* response of red blood cells (rbc) from yellowfin tuna (*Thunnus albacares*) and skipjack tuna (*Katsuwonus pelamis*) to catecholamines.

Tuna rbc had a typical response to catecholamines, indicated by a rapid decrease in pH_e . Amiloride reduced the response, whereas DIDS enhanced both the decrease in pH_e and the increase pH_i . Changes in plasma $[\text{Na}^+]$, $[\text{Cl}^-]$, and $[\text{K}^+]$ were consistent with the hypothesis that tuna rbc have a Na^+/H^+ antiporter similar to that described for other teleost rbc. Rbc from both tuna species were more responsive to noradrenaline than adrenaline. At identical catecholamine concentrations, the decrease in pH_e was greater in skipjack tuna blood, the more active of the two tuna species.

Based on changes in pH_e , the response of rbc to catecholamines from both tuna species was less than that of rainbow trout (*Oncorhynchus mykiss*) rbc, but greater than that of cod (*Gadus morhua*) rbc. Noradrenaline had no measurable influence on the O_2 affinity of skipjack tuna blood and only slightly increased the O_2 affinity of

yellowfin tuna blood. Our results, therefore, do not support our original hypothesis. The catecholamine response of rbc from high-energy-demand teleosts (i.e., tunas) is not enhanced compared to other teleosts. There are data on changes in cardio-respiratory function in tunas caused by acute hypoxia and modest increases in activity, but there are no data on the changes in cardio-respiratory function in tunas accompanying the large increases in metabolic rate seen during recovery from exhaustive exercise. However, we conclude that during those instances where high rates of O₂ delivery to the tissues are needed, tunas' ability to increase cardiac output, ventilation volume, blood O₂ carrying capacity, and effective respiratory (i.e., gill) surface area are probably more important than are the responses of rbc to catecholamines.

We also use our data to investigate the extent of the Haldane effect and its relationship to blood O₂ and CO₂ transport in yellowfin tuna. Yellowfin tuna blood shows a large Haldane effect; pH_i increases 0.20 units during oxygenation. The largest change in pH_i occurs between 40-100% O₂ saturation, indicating that yellowfin tuna, like other teleosts, fully exploit the Haldane effect over the normal physiological range of blood O₂ saturation.

Environmental preferences of yellowfin tuna (*Thunnus albacares*) at
the northern extent of their range.

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We used acoustic telemetry to examine the small-scale movement patterns of yellowfin (*Thunnus albacares*) in the California Bight at the northern extent of their range. Oceanographic profiles of temperature, oxygen currents and fluorometry were used to determine the relationship between movements and environmental features. Three yellowfin tuna (8 to 16 kg) were tracked for 2 to 3 d. All three fish spent the majority of their time above the thermocline (18 to 45 m in depth) in water temperatures > 17.5 C. In the California Bight, yellowfin tun have a limited vertical distribution due to the restriction imposed by temperature. The three fish made periodic short dives below the thermocline (60 to 80 m), encountering cooler water temperatures (> 11 C). When swimming in northern latitudes, the depth of the mixed layer largely defines the spatial distribution of yellowfin tuna within the water column. Yellowfin tuna prefer to spend most of their time just above the top of thermocline. Oxygen profiles indicated that the tunas encountered oceanic water masses that ranged most often from 6.8 to 8.6 mg O₂ l⁻¹, indicating no limitation due to oxygen concentrations. The yellowfin tuna traveled at speeds ranging from 0.46 to 0.90 m s⁻¹ (0.9 to 1.8 knots h⁻¹) and frequently exhibited and oscillatory diving pattern previously suggested to be a possible strategy for conserving energy during swimming.

Effects of Open- and Closed-system Temperature Change on Blood O₂ Binding in Bigeye Tuna (Thunnus obesus), a High-Energy-Demand Teleost with an Unusually High Blood O₂ Affinity

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Bigeye tuna blood displayed an unusually low P₅₀ (i.e., the PO₂ at which the blood is 50% saturated) (1.6-2.0 kPa; 12-15 mm Hg when equilibrated with 0.5% CO₂) compared to the P₅₀ of yellowfin tuna (Thunnus albacares, Bonnaterre) or skipjack tuna (Katsuwonus pelamis, Linnaeus) blood (2.8-3.1 kPa; 21-23 mm Hg when equilibrated with 0.5% CO₂). These data strongly suggest that bigeye tuna are more tolerant of hypoxia than skipjack and yellowfin tunas and agree with similar conclusions derived from capture-depth data and whole animal physiology studies. We also found bigeye tuna (Thunnus obesus, Lowe) blood O₂ affinity (*in vitro*) to be essentially temperature-independent when subjected to a 10 C open-system temperature change, but to have enhanced temperature sensitivity when subjected to a 10 C closed-system temperature change. In other words, bigeye tuna blood has a significantly enhanced Bohr effect when subjected to the increases in PCO₂ and decreases in plasma pH that inevitably accompany closed-system temperature shifts. Therefore, when the blood reaches the warm muscles in bigeye tuna, the elevated Bohr effect and resultant large increase in P₅₀ seen during closed-system temperature change ensure adequate rates of O₂ off-loading in the tissues of this high-energy-demand teleost.

Horizontal movements, depth distribution, and the physical environment of large adult yellowfin tuna (Thunnus albacares) near the Hawaiian Islands recorded using ultrasonic telemetry, with implications for their physiological ecology

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We measured the horizontal and vertical movements of five adult yellowfin tuna (Thunnus albacares, estimated body mass 64-93 kg) near the main Hawaiian Islands, while simultaneously gathering data on oceanographic conditions and currents. Fish movements were recorded using ultrasonic depth sensitive transmitters; depth-temperature and depth-oxygen profiles were measured with vertical conductivity-temperature-depth (CTD) casts; the current velocity field was surveyed using an acoustic Doppler current profiler. Large adult yellowfin tuna spent approximately 60-80% of their time either in or immediately below the relatively uniform temperature surface layer (i.e., above 100 m), a behavior pattern similar to that seen in juvenile (2-5 kg) yellowfin tuna, blue marlin (Makaira nigricans), and striped marlin (Tetrapturus audax) tracked in the same area. In all three species, maximum swimming depths appear to be limited by water temperatures 8 C colder than surface layer water temperature. Therefore, neither the large body mass of

adult yellowfin tunas, nor the presence of vascular counter-current heat exchangers in tunas, appear to permit greater vertical mobility or the ability to remain for extended periods below the thermocline. Like juvenile yellowfin tuna, but unlike blue and striped marlin tracked near the main Hawaiian Islands, adult yellowfin tuna remained within 10 nautical miles (18.5 km) of the coast and became associated with floating objects, including anchored fish aggregating devices (FADs) and the tracking vessel. As previously shown for juvenile yellowfin tuna, large adult yellowfin appear capable of learning the locations of FADs, repeatedly re-visiting the same FAD, and navigating precisely between FADs up to 18 km (10 nautical miles) apart. The median speed over ground of adult yellowfin tuna ranged from 72-154 cm s^{-1} (1.4-3.0 knots). Neither speed nor direction appeared strongly influenced by currents.