



## Melatonin Binding Sites in the Goldfish Retina

Authors: Iigo, Masayuki, Ohtani-Kaneko, Ritsuko, Hara, Masayuki, Hirata, Kazuaki, and Aida, Katsumi

Source: Zoological Science, 14(4) : 601-607

Published By: Zoological Society of Japan

URL: <https://doi.org/10.2108/zsj.14.601>

---

BioOne Complete ([complete.BioOne.org](https://complete.BioOne.org)) is a full-text database of 200 subscribed and open-access titles in the biological, ecological, and environmental sciences published by nonprofit societies, associations, museums, institutions, and presses.

Your use of this PDF, the BioOne Complete website, and all posted and associated content indicates your acceptance of BioOne's Terms of Use, available at [www.bioone.org/terms-of-use](https://www.bioone.org/terms-of-use).

Usage of BioOne Complete content is strictly limited to personal, educational, and non-commercial use. Commercial inquiries or rights and permissions requests should be directed to the individual publisher as copyright holder.

---

BioOne sees sustainable scholarly publishing as an inherently collaborative enterprise connecting authors, nonprofit publishers, academic institutions, research libraries, and research funders in the common goal of maximizing access to critical research.

## Melatonin Binding Sites in the Goldfish Retina

Masayuki Iigo<sup>1\*</sup>, Ritsuko Ohtani-Kaneko<sup>1</sup>, Masayuki Hara<sup>1</sup>,  
Kazuaki Hirata<sup>1</sup> and Katsumi Aida<sup>2</sup>

<sup>1</sup>Department of Anatomy, St. Marianna University School of Medicine,  
Miyamae, Kawasaki 216, Japan

<sup>2</sup>Laboratory of Aquatic Animal Physiology, Graduate School of Agricultural  
and Life Sciences, The University of Tokyo,  
Bunkyo-ku, Tokyo 113, Japan

**ABSTRACT**—Melatonin binding sites in the goldfish retina were characterized by radioreceptor assay using 2-[<sup>125</sup>I]iodomelatonin as the radioligand. The specific binding to goldfish retinal membranes is rapid, stable, saturable and reversible. Saturation studies demonstrated that 2-[<sup>125</sup>I]iodomelatonin binds to a single class of sites with an affinity constant ( $K_d$ ) of  $61.9 \pm 5.7$  pM, a total binding capacity ( $B_{max}$ ) of  $6.52 \pm 0.79$  fmol/mg protein and Hill coefficients ( $n_H$ ) of  $1.07 \pm 0.03$  (mean  $\pm$  SEM,  $n=6$ ). Competition experiments with various indoles and neurotransmitters revealed the following order of affinities: 2-iodomelatonin > melatonin > 6-hydroxymelatonin > 5-methoxytryptamine = *N*-acetylserotonin > 5-methoxytryptophol. The other indoles and neurotransmitters tested were much less effective. The order resembles with those reported for the goldfish brain and the ML-1 subtype melatonin receptors in vertebrates. Co-incubation of retinal membranes with a non-hydrolyzable GTP analog, guanosine 5'-*O*-(3-thiotriphosphate), significantly reduced the specific binding. These results suggest that in the goldfish, ocular melatonin plays neuromodulatory roles in the retina via G protein-coupled melatonin receptors with picomolar affinity.

### INTRODUCTION

Melatonin is synthesized in the pineal organ and the retina of vertebrates in a rhythmic fashion with peak production during the dark phase of light-dark (LD) cycles. Melatonin produced in the pineal organ is secreted into the blood and/or the cerebro-spinal fluid and acts as a time keeping hormone that regulates circadian and seasonal rhythms (for review, see Underwood and Goldman, 1987). Melatonin produced in the retina, on the other hand, is considered to act within the retina itself. Melatonin is known to affect several aspects of retinal physiological processes such as dopamine release, retinomotor movements, disc shedding of photoreceptor outer segments, aggregation of the retinal pigment epithelium and sensitivity of horizontal cells (for review, see Pang and Allen, 1986; Cahill *et al.*, 1991).

The actions of melatonin are thought to be mediated through its specific receptors. Although several attempts have been made to characterize them using [<sup>3</sup>H]melatonin as a radioligand, only the binding sites with low (nanomolar) affinity were labeled (Cohen *et al.*, 1978; Cardinali *et al.*, 1979; Niles *et al.*, 1979; Gern *et al.*, 1980; Wiechmann *et al.*, 1986). The physiological functions of these sites still remain unclear. However, introduction of a melatonin agonist, 2-[<sup>125</sup>I]-

iodomelatonin with high specific radioactivity (Vakkuri *et al.*, 1984), enables us to characterize melatonin binding sites with picomolar affinity by radioreceptor assay and *in vitro* autoradiography. These sites are considered as functional melatonin receptors in various tissues including the central nervous system and peripheral tissues (for review, see Dubocovich, 1988,1995; Pang *et al.*, 1993; Morgan *et al.*, 1994). In the vertebrate retina, melatonin binding sites with picomolar affinity were identified in mammals, birds, reptiles and amphibians (Dubocovich and Takahashi, 1987; Vaněček, 1988; Laitinen and Saavedra, 1990; Blazynski and Dubocovich, 1991; Chong and Sugden, 1991; Lu *et al.*, 1991; Wiechmann and Wirsig-Wiechmann, 1991, 1994; Skene *et al.*, 1993; Failace *et al.*, 1995; James *et al.*, 1995).

In teleosts, melatonin is produced in the retina (Quay, 1965; Gern and Ralph, 1979; Wiechmann and Hollyfield, 1988; Nowak *et al.*, 1989; Falcón and Collin, 1991; Grace *et al.*, 1991; Cahill, 1996; Iigo *et al.*, 1997a) and known to affect retinal rhythmic processes (Chèze and Ali, 1976; Mangel and Wong, 1996) as well as in other vertebrate classes. Thus, it is probable that melatonin receptors exist in the teleostean retina. However, to our knowledge, melatonin binding sites with picomolar affinity have not yet identified in the retina of fishes.

In order to obtain more insights on the physiological functions of melatonin in the fish retina, in the present study, melatonin binding sites in the retina of the goldfish (*Carassius auratus*) were characterized by radioreceptor assay using 2-

\* Corresponding author: Tel. +81-44-977-8111 ext. 3629;  
FAX. +81-44-976-7083.

[<sup>125</sup>I]iodomelatonin as the radioligand. This fish was selected as our experimental model because we have studied the regulation of melatonin production in the pineal organ and eye, and characteristics and regulation of melatonin binding sites in the brain in this species (Kezuka *et al.*, 1992; Iigo *et al.*, 1994a,b, 1995, 1997a,b).

## MATERIALS AND METHODS

### Chemicals

2-[<sup>125</sup>I]iodomelatonin (specific radioactivity, 2,000–2,200 Ci/mmol) was obtained from Amersham (Buckinghamshire, England) or New England Nuclear (Boston, MA). Unlabeled 2-iodomelatonin was obtained from Research Biochemicals Inc. (Natick, MA). The other indole derivatives, norepinephrine, polyethylenimine, and guanosine 5'-O-(3-thiotriphosphate) (GTP $\gamma$ S; tetralithium salt) were obtained from Sigma (St. Louis, MO). Acetylcholine was obtained from Nacalai Tesque, Inc. (Kyoto, Japan). Ordinary chemicals were obtained from commercial sources.

### Goldfish

The goldfish (61–164 g in body weight) purchased from a local dealer were maintained in experimental aquaria under LD cycles of 12 hr:12 hr (lights on 06.00–18.00) with controlled temperature at 24–25°C for at least two weeks. Illumination (300–500 lx at the water surface) was supplied by a white fluorescent bulb (10 W) for the light phase. Fish were fed commercial trout pellets.

The goldfish were anesthetized with 2-phenoxyethanol (0.6 ml/l) and decapitated during the light phase (11.00–16.00) when ocular melatonin contents are low (Iigo *et al.*, 1994a, 1997a). The retina (neural retina with the pigment epithelium) was dissected out, immediately frozen on dry ice, and stored at –80°C until used.

### Membrane preparation and binding assay

Membrane preparation and binding assay were performed according to the procedure as previously described (Iigo *et al.*, 1994b) unless otherwise stated. Briefly, the retina was homogenized in 50 mM Tris-HCl buffer (pH 7.5), centrifuged (40,000  $\times$  g for 20 min at 4°C). The pellet was resuspended in the buffer and centrifuged for the second time. The pellet was used for binding assay. Incubation was performed in a total volume of 200  $\mu$ l and the binding of 2-[<sup>125</sup>I]iodomelatonin was routinely measured in duplicate after incubation at 25°C for 1.5 hr with the exception of kinetic studies where incubation duration and temperature varied. Protein contents in the incubation mixture were determined by the method of Bradford (1976) with bovine  $\gamma$ -globulin as a standard. Nonspecific binding was defined as the binding in the presence of 10  $\mu$ M melatonin. Specific binding was calculated by subtracting nonspecific binding from total binding and expressed as fmol/mg protein.

### Identification of bound radioligand

Stability of 2-[<sup>125</sup>I]iodomelatonin during the incubation period was examined since melatonin is known to be metabolized in the eye of nonmammalian vertebrates including the goldfish (Grace *et al.*, 1991). After filtration of a binding assay, filters were removed and extracted with methanol (2 ml). The methanol extract was evaporated under reduced pressure to a volume of 100  $\mu$ l. An aliquot of this extract (50  $\mu$ l) was applied to a silica gel plate for thin layer chromatography (TLC) (Whatman LK6F, Whatman International Ltd., Maidstone, England). Melatonin (10  $\mu$ g) and 2-iodomelatonin (10  $\mu$ g) were also applied as tracers. Chromatograms were developed with ethyl acetate for 10 cm. The position of melatonin and 2-iodomelatonin on the TLC plate was determined by fluorescence during exposure to UV lights and the  $R_f$  values were calculated. Radioactivity of sections of silica gel (1 cm) were counted in a  $\gamma$ -counter. The peak radioactivity in the

extracts of the bound radioligand was compared with the position of 2-iodomelatonin.

### Characterization and GTP $\gamma$ S modulation of melatonin binding sites in the goldfish retina

Saturation studies were performed using a range of 2-[<sup>125</sup>I]iodomelatonin concentration from 4.4 to 269.9 pM. Kinetic and competition studies were performed using a 2-[<sup>125</sup>I]iodomelatonin concentration of 49.9 and 49.6 pM, respectively. To study the effects of GTP $\gamma$ S on melatonin binding sites in the goldfish retina, the specific binding of 2-[<sup>125</sup>I]iodomelatonin (68.9 pM) was determined in the presence or absence of GTP $\gamma$ S (10<sup>–4</sup> M).

### Data analysis

Data obtained from kinetic, saturation and competition experiments were analyzed as previously described (Iigo *et al.*, 1994b) to calculate association rate constants ( $k_1$ ), dissociation rate constants ( $k_{-1}$ ),  $K_d$ ,  $B_{max}$ ,  $n_H$  and  $K_i$  values. Correlation between the specific binding and the protein concentration in the incubation mixture, and between log  $K_i$  values of some indoles obtained in the present study and those reported for the goldfish brain (Iigo *et al.*, 1994b) was analyzed by linear-regression analysis. The specific binding in the GTP $\gamma$ S-treated group was compared with the vehicle-treated control by paired *t*-test.

## RESULTS

### Binding conditions

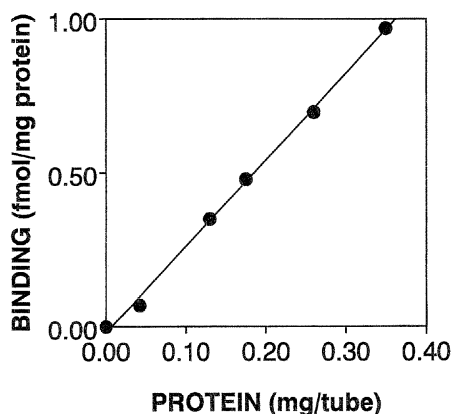
At first, the time course of the association of 2-[<sup>125</sup>I]-iodomelatonin (50.0 pM) to goldfish retinal membranes at 0, 25 and 37°C was compared (data not shown). The specific binding at equilibrium was similar at 0 and 25°C but the equilibrium was reached faster at 25°C (1 hr) than at 0°C (12 hr). At 37°C, the specific binding did not show a steady state. Therefore, further experiments were performed at 25°C.

In a preliminary study, retinal homogenates were prepared in 50 mM Tris-HCl buffer (pH 7.5) containing 0.32 M sucrose and fractionated by differential centrifugation at 4°C to yield a crude nuclear pellet ( $P_1$ , 1,000  $\times$  g for 10 min), a crude mitochondrial pellet ( $P_2$ , 40,000  $\times$  g for 10 min), and a crude microsomal pellet ( $P_3$ , 100,000  $\times$  g for 60 min) to study the intracellular distribution of melatonin binding sites. The specific binding of 2-[<sup>125</sup>I]iodomelatonin (50.0 pM) in these membrane fractions was found to be greatest in the  $P_2$  fraction (7.35 fmol/mg protein, 42% of the specific binding in the total retinal membranes) as compared to the  $P_1$  fraction (2.01 fmol/mg protein, 28%) and the  $P_3$  fraction (4.40 fmol/mg protein, 30%). These results indicate that the 40,000  $\times$  g pellet used in the present study contained 70% of the specific binding in the total retinal membranes.

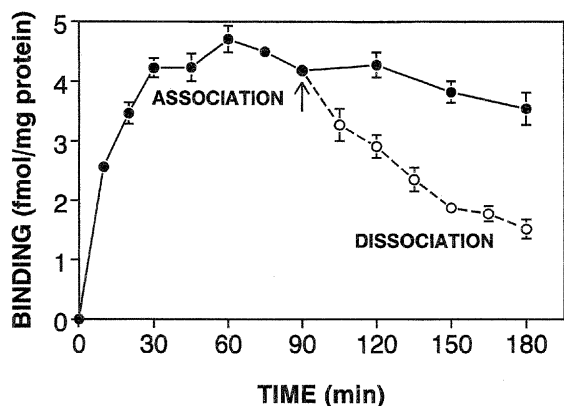
Linear regression analysis revealed that there was a significant relationship between the specific binding of 2-[<sup>125</sup>I]iodomelatonin (50.0 pM) and the protein concentration in the incubation mixture at least up to 0.35 mg protein/tube ( $r=0.999$ ,  $P<0.001$ ,  $n=6$ ; Fig. 1).

### Identification of bound radioligand

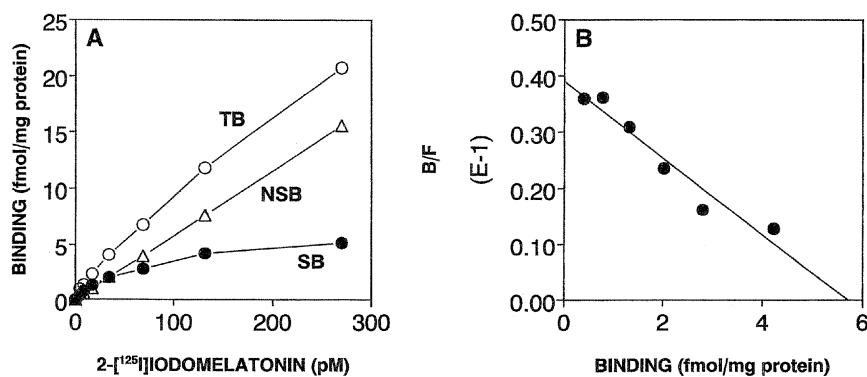
Radioactivity of the bound radioligand, extracted from filters after a binding assay with methanol, comigrated with synthetic 2-iodomelatonin. The  $R_f$  values for synthetic melatonin



**Fig. 1.** The relationship between the specific binding of 2-[<sup>125</sup>I]iodomelatonin (50.0 pM) to goldfish retinal membranes and the protein concentration in the incubation mixture. Values shown are means from a experiment performed in duplicate. A significant relationship was obtained between the two at least up to 0.35 mg protein/tube ( $r=0.999$ ,  $P<0.001$ ,  $n=6$ ).



**Fig. 2.** The time course of the association (closed circles) and dissociation (open circles) of 2-[<sup>125</sup>I]iodomelatonin (49.9 pM) to goldfish retinal membranes at 25°C. Values represent the means  $\pm$  SEM ( $n=6$ ). A steady state was reached at 1 hr and stable during 1–3 hr. The specific binding was reversible upon the addition of 8  $\mu$ M melatonin (arrow).



**Fig. 3.** (A) A saturation curve of 2-[<sup>125</sup>I]iodomelatonin (4.4–269.9 pM) binding to goldfish retinal membranes. Each point represents the mean of duplicate determinations from a representative experiment of six such studies. Nonspecific binding (NSB) was measured in the presence of 10  $\mu$ M melatonin. Specific binding (SB) is defined as total binding (TB) minus nonspecific binding. (B) A Scatchard plot of the data shown in (A). In this case, the  $K_d$ ,  $B_{max}$  and  $n_H$  values were 53.1 pM, 5.71 fmol/mg protein and 1.03, respectively.

and 2-iodomelatonin was 0.32 and 0.55, respectively. Peak radioactivity (>96% of total) recovered between  $R_f$  values of 0.5 and 0.6.

#### Kinetic study

At 25°C, the specific binding was rapid, stable and reversible (Fig. 2). The  $k_1$  determined from the pseudo-first-order plot was  $4.69 \times 10^8 \pm 0.74 \times 10^8 \text{ M}^{-1} \text{ min}^{-1}$  ( $n=6$ ). The specific binding was stable from 1–3 hr of incubation. After 1.5 hr of incubation with 2-[<sup>125</sup>I]iodomelatonin, dissociation was initiated by addition of melatonin (8  $\mu$ M) to some tubes. The  $k_{-1}$  calculated from the first-order regression analysis was  $1.05 \times 10^{-2} \pm 0.08 \times 10^{-2} \text{ min}^{-1}$  ( $n=6$ ). The kinetic dissociation constant calculated from the ratio  $k_{-1}/k_1$  was  $24.2 \pm 3.0 \text{ pM}$ .

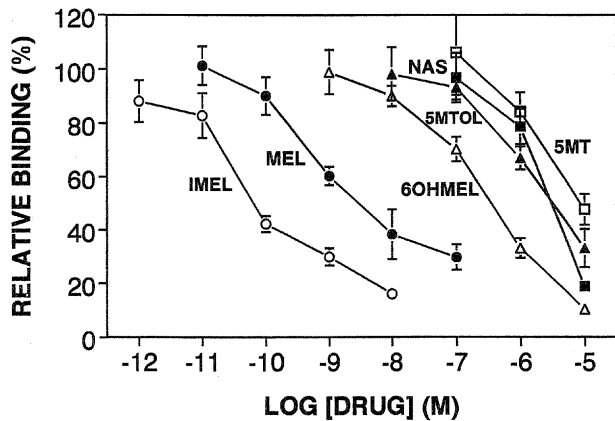
#### Saturation study

Saturation experiments using a range of 2-[<sup>125</sup>I]iodomelatonin concentrations from 4.4 to 269.9 pM demonstrated that the specific binding reached a plateau at approximately 130 pM (Fig. 3A). Scatchard analysis of the data (Fig. 3B) revealed that 2-[<sup>125</sup>I]iodomelatonin binds to a single class of sites with the  $K_d$  of  $61.9 \pm 5.7 \text{ pM}$ , the  $B_{max}$  of  $6.52 \pm 0.79 \text{ fmol/mg protein}$ , the  $n_H$  of  $1.07 \pm 0.03$  ( $n=6$ ).

#### Specificity

Specificity of melatonin binding sites in the goldfish retina is shown in Fig. 4 and Table 1. Competition experiments carried out using a concentration of 2-[<sup>125</sup>I]iodomelatonin (49.6 pM) with several indole compounds and neurotransmitters revealed the following order of potency to inhibit the specific binding: 2-iodomelatonin > melatonin > 6-hydroxymelatonin > 5-methoxytryptamine = *N*-acetylserotonin > 5-methoxytryptophol. Even at a concentration of  $10^{-4} \text{ M}$ , 5-methoxyindole-3-acetic acid and serotonin exhibited less than 50% inhibition, and 5-hydroxytryptophol, 5-hydroxyindole-3-acetic acid, norepinephrine and acetylcholine showed no inhibition (data not shown).

Linear regression analysis demonstrated a significant correlation between the log  $K_i$  values obtained in the present



**Fig. 4.** Competition curves for inhibition of 2-[<sup>125</sup>I]iodomelatonin (49.6 pM) binding to goldfish retinal membranes by various indole derivatives. Values represent the means  $\pm$  SEM (n=3). The membrane preparations were incubated with 2-[<sup>125</sup>I]iodomelatonin (49.6 pM) and various concentrations of 2-iodomelatonin (IMEL), melatonin (MEL), 6-hydroxymelatonin (6OHMEL), 5-methoxytryptophol (5MTOL), *N*-acetylserotonin (NAS), and 5-methoxytryptamine (5MT). The  $K_i$  values were calculated from these data are shown in Table 1.

**Table 1.** Specificity of melatonin binding sites in the goldfish retina

Drug	<sup>a</sup> $K_i$ (nM)	<sup>b</sup> Affinity ratio to melatonin
2-Iodomelatonin	0.043 $\pm$ 0.014	0.014
Melatonin	3.12 $\pm$ 1.23	1
6-Hydroxymelatonin	234 $\pm$ 17	75
5-Methoxytryptamine	2140 $\pm$ 320	690
<i>N</i> -Acetylserotonin	2370 $\pm$ 700	760
5-Methoxytryptophol	4830 $\pm$ 100	1550
5-Methoxyindole-3-acetic acid	>79000	>141000
Serotonin	>79000	>141000
5-Hydroxytryptophol	>79000	>141000
5-Hydroxyindole-3-acetic acid	>79000	>141000
Acetylcholine	>79000	>141000
Norepinephrine	>79000	>141000

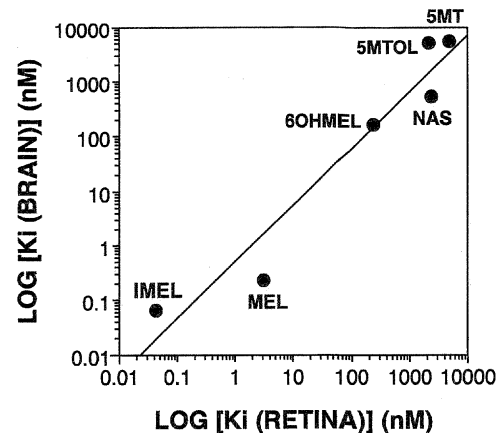
<sup>a</sup>Relative inhibition for the binding of 2-[<sup>125</sup>I]iodomelatonin (49.6 pM) to retinal membranes was determined for 3-5 concentrations of competing drugs. The  $K_i$  values were calculated from the  $IC_{50}$  values obtained from the competition studies as previously described (Iigo *et al.*, 1994b). Results are the mean  $\pm$  SEM (n=3).

<sup>b</sup>The ratio of the  $K_i$  value of competing drug versus the  $K_i$  value of melatonin.

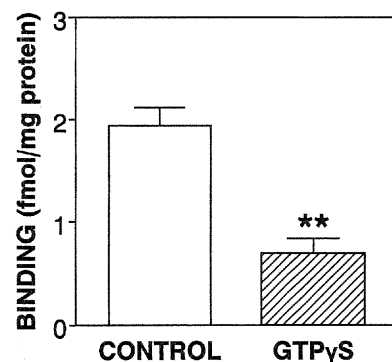
study and those reported for the goldfish brain (slope=1.038,  $r=0.965$ ,  $P<0.01$ ,  $n=6$ ; Fig. 5).

#### Effects of GTP $\gamma$ S

Effects of GTP $\gamma$ S ( $10^{-4}$  M) on the specific binding of 2-[<sup>125</sup>I]iodomelatonin (68.9 pM) to goldfish retinal membranes are exhibited in Fig. 6. The specific binding of the GTP $\gamma$ S-treated group was significantly reduced as compared with the vehicle-treated control ( $P<0.01$ ).



**Fig. 5.** Correlation between the affinities of melatonin analogs for melatonin binding sites in the retina and brain of the goldfish. The  $K_i$  values for the goldfish brain are taken from Iigo *et al.* (1994b). Linear regression analysis after logarithmic transformation of the data revealed a significant correlation (slope=1.038,  $r=0.965$ ,  $P<0.01$ ,  $n=6$ ). Abbreviations of the compounds are the same as in Fig. 4.



**Fig. 6.** Effects of GTP $\gamma$ S ( $10^{-4}$  M) on the specific binding of 2-[<sup>125</sup>I]iodomelatonin (68.9 pM) to goldfish retinal membranes. Values represent the means  $\pm$  SEM (n=5). The control group was treated with vehicle (distilled water). Significance: \*\*,  $P<0.01$  compared with the control values (paired *t*-test).

## DISCUSSION

Presence of melatonin and its synthesizing enzymes have been demonstrated in the eye of several teleost species (Quay, 1965; Gern and Ralph, 1979; Wiechmann and Hollyfield, 1988; Nowak *et al.*, 1989; Falc3n and Collin, 1991; Grace *et al.*, 1991; Cahill, 1996; Iigo *et al.*, 1997a,c,d; S3nchez-V3zquez *et al.*, 1997). To investigate the sites of melatonin action in the fish retina, in the present study, existence of melatonin binding sites in the goldfish retina was investigated by radioreceptor assay using 2-[<sup>125</sup>I]iodomelatonin as the radioligand.

We successfully detected the specific binding of 2-[<sup>125</sup>I]iodomelatonin to the goldfish retinal membranes as in the goldfish brain membranes (Iigo *et al.*, 1994b). The nonspecific binding was relatively high as compared with those in the brain. This might be caused by the binding of the radioligand

to the melanosomes in the retinal pigmented epithelium (James *et al.*, 1995).

The specific binding of 2-[<sup>125</sup>I]iodomelatonin to goldfish retinal membranes fulfills all the criteria for binding to a receptor site: the binding was rapid, stable, saturable, reversible, and of high specificity, low capacity, and high affinity. The radioligand was stable during the incubation period and appeared to label a single class of binding sites as is evident from linear Scatchard plots, monophasic inhibition curves and the  $n_H$  close to unity. The  $K_D$  values obtained from the kinetic and saturation experiments and the  $K_i$  values obtained from the competition study were consistent with picomolar affinity as those in the goldfish brain (Martinoli *et al.*, 1991; Iigo *et al.*, 1994b, 1995). These values are also well within the physiological range of ocular melatonin contents in the goldfish (0.1–2.5 ng/eye) (Iigo *et al.*, 1994a, 1997a), suggesting that the sites labeled with 2-[<sup>125</sup>I]iodomelatonin are physiological melatonin receptors as in the retina of chicken and rabbit (Dubocovich and Takahashi, 1987; Blazynski and Dubocovich, 1991).

Pharmacological specificity of melatonin binding sites in the goldfish retina was determined using several indoles and neurotransmitters. The results indicate that the binding sites are highly specific for 2-iodomelatonin and melatonin. Precursors and metabolites of melatonin were much less effective. Furthermore, compounds known to act at serotonergic, adrenergic or cholinergic sites were ineffective. The specificity of melatonin binding sites in the retina and brain of the goldfish are highly correlated, and resembles with those of the ML-1 but not with the ML-2 melatonin receptor subtype (Dubocovich, 1988, 1995). These results indicate that melatonin binding sites in the goldfish retina and brain belong to the ML-1 subtype.

During the course of this study, cDNAs encoding melatonin receptors with picomolar affinity were cloned. The results indicate that there are at least three subtypes of melatonin receptors among the ML-1 subtype, namely Mel<sub>1a</sub>, Mel<sub>1b</sub> and Mel<sub>1c</sub> subtypes (for review, see Reppert and Weaver, 1995). However, no melatonin analogue is available to distinguish differences in the pharmacological properties among these three subtypes (Pickering *et al.*, 1996). Thus, molecular biological studies are necessary to characterize the subtype(s) of melatonin receptors expressed in a given tissue. As far as teleost fish are concerned, 5 different DNA fragments of putative melatonin receptors (2 clones belong to the Mel<sub>1a</sub>, 2 to the Mel<sub>1b</sub> and 1 to the Mel<sub>1c</sub> subtype) were isolated from genomic DNA of the zebrafish (Reppert *et al.*, 1995, 1996). However, it is still controversial whether these are functional melatonin receptors and in which tissues they are expressed. Thus, further molecular biological approach will be required to determine which subtype is expressed in the goldfish retina.

In the present study, the nature of melatonin binding sites-G protein coupling was examined in the goldfish retinal membranes by the use of a non-hydrolyzable GTP analog, GTP $\gamma$ S, because several authors have failed to detect the effects of GTP and its analogues on 2-[<sup>125</sup>I]iodomelatonin binding to reti-

nal membranes (Dubocovich and Takahashi, 1987; Chong and Sugden, 1991). The treatment of GTP $\gamma$ S significantly reduced the specific binding of 2-[<sup>125</sup>I]iodomelatonin to the goldfish retinal membranes, indicating that melatonin binding sites in the goldfish retina are coupled to G protein as those in the goldfish brain (Iigo *et al.*, 1997b) and in the retina, brain and pars tuberalis of other vertebrate species (Skene *et al.*, 1993; Morgan *et al.*, 1994; James *et al.*, 1995). These results are also consistent with the recent results of cDNA cloning: melatonin receptors are members of the G protein-coupled receptor superfamily that contain seven hydrophobic segments (Reppert and Weaver, 1995). Further studies to identify the type(s) of G protein and the effector enzyme associated with melatonin receptor-G protein complex will help to elucidate the function of melatonin in the goldfish retina.

In the retina of rabbit, chicken, lizard and frog, melatonin binding sites were localized mainly in the inner plexiform layer as revealed by *in vitro* autoradiography (Laitinen and Saavedra, 1990; Blazynski and Dubocovich, 1991; Wiechmann and Wirsig-Wiechmann, 1991, 1994). Furthermore, localization of functional melatonin receptors are reported in the iris-ciliary processes of rabbit and in the retinal pigmented epithelium of human and rat (Osborne and Chidlow, 1994; Nash and Osborne, 1995). These structures may be possible sites of melatonin action in the goldfish retina. By the use of an *in vitro* autoradiographic technique, we have localized the specific binding in the neural retina of the goldfish (our unpublished results). However, precise localization was not apparent because of low resolution caused by high non-specific binding in the retinal pigmented epithelium. Further studies should be required to elucidate this subject.

In the goldfish, melatonin produced in the retina does not contribute to its blood levels and is metabolized in the eye (Quay, 1965; Grace *et al.*, 1991; Kezuka *et al.*, 1992; Iigo *et al.*, 1997a), suggesting that melatonin may have local neuromodulatory roles in the retina. Visual sensitivity and inputs from photoreceptor to horizontal cells have been reported to exhibit circadian rhythms in the goldfish (Bassi and Powers, 1987; Wang and Mangel, 1996) and melatonin is considered to be involved in the regulation of these retinal events (Iigo *et al.*, 1997a). Recently, melatonin is proved to increase rod input but decrease cone input to the L-type cone horizontal cells in the goldfish (Mangel and Wong, 1996). These processes may be mediated by high-affinity melatonin binding sites characterized in the present study.

## ACKNOWLEDGMENTS

This study was supported in part by Grants-in-Aid from the Ministry of Agriculture, Forestry, and Fisheries (BMP 97-II-2-1) and from the Ministry of Education, Science, Sports and Culture of Japan.

## REFERENCES

- Bassi CJ, Powers MK (1987) Circadian rhythm in goldfish visual sensitivity. *Invest Ophthalmol Vis Sci* 28: 1811–1815
- Blazynski C, Dubocovich ML (1991) Localization of 2-

- [<sup>125</sup>I]iodomelatonin binding sites in mammalian retina. *J Neurochem* 56: 1873–1880
- Bradford MM (1976) A rapid and sensitive method for the quantitation of microgram quantities of protein utilizing the principle of protein-dye binding. *Anal Biochem* 72: 248–254
- Cahill GM (1996) Circadian regulation of melatonin production in cultured zebrafish pineal and retina. *Brain Res* 708: 177–181
- Cahill GM, Grace MS, Besharse JC (1991) Rhythmic regulation of retinal melatonin: Metabolic pathways, neurochemical mechanisms, and ocular circadian clock. *Cell Mol Neurobiol* 11: 529–560
- Cardinali DP, Vacas MI, Boyer EE (1979) Specific binding of melatonin in bovine brain. *Endocrinology* 105: 437–441
- Chéze G, Ali MA (1976) Rôle de l'épiphyse dans la migration du pigment épithélial rétinien chez quelques Téléostéens. *Can J Zool* 54: 475–481
- Chong N, Sugden D (1991) Guanine nucleotide regulates 2-[<sup>125</sup>I]iodomelatonin binding sites in chick retinal pigment epithelium but not in neural retina. *J Neurochem* 57: 685–689
- Cohen M, Roselle D, Chabner B, Schmidt TJ, Lipmann M (1978) Evidence for a cytoplasmic melatonin receptor. *Nature* 274: 894–895
- Dubocovich ML (1988) Pharmacology and function of melatonin receptors. *FASEB J* 2: 2765–2773
- Dubocovich ML (1995) Melatonin receptors: are there multiple subtypes? *Trends Pharmacol Sci* 16: 50–56
- Dubocovich ML, Takahashi JS (1987) Use of 2-[<sup>125</sup>I]iodomelatonin to characterize melatonin binding sites in chicken retina. *Proc Natl Acad Sci USA* 84: 3916–3920
- Failace MP, De Las Heras MA, Sarmiento MIK, Rosenstein RE (1995) Daily variation in 2-[<sup>125</sup>I]melatonin specific binding in the golden hamster retina. *Neuroreport* 7: 141–144
- Falcón J, Collin JP (1991) Pineal-retinal relationships: rhythmic biosynthesis and immunocytochemical localization of melatonin in the retina of the pike (*Esox lucius*). *Cell Tissue Res* 265: 601–609
- Gern WA, Ralph CL (1979) Melatonin synthesis by the retina. *Science* 204: 183–184
- Gern WA, Gorell TA, Owens DW (1980) Melatonin and pigment cell rhythmicity. *Adv Biosci* 29: 223–233
- Grace MS, Cahill GM, Besharse JC (1991) Melatonin deacetylation: retinal vertebrate class distribution and *Xenopus laevis* tissue distribution. *Brain Res* 559: 56–63
- Iigo M, Kezuka H, Suzuki T, Tabata M, Aida K (1994a) Melatonin signal transduction in the goldfish, *Carassius auratus*. *Neurosci Biobehav Rev* 18: 563–569
- Iigo M, Kobayashi M, Ohtani-Kaneko R, Hara M, Hattori A, Suzuki T, Aida K (1994b) Characteristics, day-night changes, subcellular distribution and localization of melatonin binding sites in the goldfish brain. *Brain Res* 644: 213–220
- Iigo M, Furukawa K, Hattori A, Hara M, Ohtani-Kaneko R, Suzuki T, Tabata M, Aida K (1995) Effects of pinealectomy and constant light exposure on day-night changes of melatonin binding sites in the goldfish brain. *Neurosci Lett* 197: 61–64
- Iigo M, Furukawa K, Hattori A, Ohtani-Kaneko R, Hara M, Suzuki T, Tabata M, Aida K (1997a). Ocular melatonin rhythms in the goldfish, *Carassius auratus*. *J Biol Rhythms* 12:182–192
- Iigo M, Ohtani-Kaneko R, Hara M, Hattori A, Takahashi H, Tabata M, Suzuki T, Aida K (1997b) Regulation by guanine nucleotides and cations of melatonin binding sites in the goldfish brain. *Biol Signals* 6: 29–39
- Iigo M, Sánchez-Vázquez FJ, Madrid JA, Zamora S, Tabata M (1997c) Unusual responses to light and darkness of ocular melatonin in European sea bass. *Neuroreport* 8: 1631–1635
- Iigo M, Tabata M, Aida K (1997d) Ocular melatonin rhythms in a cyprinid teleost, oikawa *Zacco platypus*, are driven by light-dark cycles. *Zool Sci* 14: 237–242
- James K, Skene DJ, Lucini V, Stankov B, Arendt J (1995) Characterisation of melatonin binding sites in the eye of the Japanese quail (*Coturnix japonica*). *Gen Comp Endocrinol* 100: 188–196
- Kezuka H, Iigo M, Furukawa K, Aida K, Hanyu I (1992) Effects of photoperiod, pinealectomy and ophthalmectomy on circulating melatonin rhythms in the goldfish, *Carassius auratus*. *Zool Sci* 9: 1047–1053
- Laitinen JT, Saavedra JM (1990) The chick retinal melatonin receptor revisited: localization and modulation of agonist binding with guanine nucleotides. *Brain Res* 528: 349–352
- Lu Y, Yuan H, Pang SF (1991) Retinal [<sup>125</sup>I]iodomelatonin binding sites in the tree shrew (*Tupaiaidae*). *Neurosci Lett* 130: 149–152
- Mangel SC, Wang Y (1996) Melatonin acts as a circadian clock regulator of rod and cone pathways in fish retina. *Soc Neurosci Abstract* 22: 2017
- Martinoli MG, Williams LM, Kah O, Titchener LT, Pelletier G (1991) Distribution of central melatonin binding sites in the goldfish (*Carassius auratus*). *Mol Cell Neurosci* 2: 78–85
- Morgan PJ, Barrett P, Howell HE, Helliwell R (1994) Melatonin receptors: Localization, molecular pharmacology and physiological significance. *Neurochem Int* 24: 101–146
- Nash MS, Osborne NN (1995) Pertussis toxin-sensitive melatonin receptors negatively coupled to adenylate cyclase associated with cultured human and rat retinal pigment epithelial cells. *Invest Ophthalmol Vis Sci* 36: 95–102
- Niles LP, Wong YW, Mishra RK, Brown GM (1979) Melatonin receptors in brain. *Eur J Pharmacol* 55: 219–220
- Nowak JZ, Zurawska E, Zawilska J (1989) Melatonin and its generating system in vertebrate retina: Circadian rhythm, effect of environmental lighting and interaction with dopamine. *Neurochem Int* 14: 397–406
- Osborne NN, Chidlow G (1994) The presence of functional melatonin receptors in the iris-ciliary processes of the rabbit eye. *Exp Eye Res* 59: 3–9
- Pang SF, Allen AE (1986) Extra-pineal melatonin in the retina: its regulation and physiological function. *Pineal Res Rev* 4: 55–95
- Pang SF, Dubocovich ML, Brown GM (1993) Melatonin receptors in peripheral tissues: A new area of melatonin research. *Biol Signals* 2: 177–180
- Pickering H, Sword S, Vonhoff S, Jones R, Sugden D (1996) Analogues of diverse structure are unable to differentiate native melatonin receptors in the chicken retina, sheep pars tuberalis and *Xenopus* melanophores. *Brit J Pharmacol* 119: 379–387
- Quay WB (1965) Retinal and pineal hydroxyindole-O-methyltransferase activity in vertebrates. *Life Sci* 4: 983–991
- Reppert SM, Weaver DR (1995) Melatonin madness. *Cell* 83: 1059–1062
- Reppert SM, Weaver DR, Cassone VM, Godson C, Kalakowski Jr LF (1995) Melatonin receptors are for the birds: Molecular analysis of two receptor subtypes differentially expressed in chick brain. *Neuron* 15: 1003–1015
- Reppert SM, Weaver DR, Ebisawa T, Mahle CD, Kalakowski Jr LF (1996) Cloning of a melatonin-related receptor from human pituitary. *FEBS Lett* 386: 219–224
- Sánchez-Vázquez FJ, Iigo M, Madrid JA, Zamora S, Tabata M (1997) Daily cycles in plasma and ocular melatonin in demand-fed sea bass, *Dicentrarchus labrax*, L. *J Comp Physiol B* (in press)
- Skene DJ, Naynaud F, Pévet P (1993) Melatonin and 5-methoxytryptophol binding sites in the retina. In "Melatonin and the Pineal Gland- from Basic Science to Clinical Application" Ed by Y Touitou, J Arendt, P Pévet, Excerpta Medica, Amsterdam, pp 87–97
- Underwood H, Goldman BD (1987) Vertebrate circadian and photoperiodic systems: role of the pineal gland and melatonin. *J Biol Rhythms* 2: 279–315
- Vakkuri O, Lamsa E, Rahkamaa E, Ruotsalainen H, Leppaluoto J

- (1984) Iodinated melatonin: Preparation and characterization of the molecular structure by mass and  $^1\text{H}$  NMR spectroscopy. *Anal Biochem* 142: 284–289
- Vaněček J (1988) Melatonin binding sites. *J Neurochem* 51: 1436–1440
- Wang Y, Mangel SC (1996) A circadian clock regulates rod and cone input to fish retinal cone horizontal cells. *Proc Natl Acad Sci USA* 93: 4655–4660
- Wiechmann AF, Bok D, Horwitz J (1986) Melatonin-binding in the frog retina: autoradiographic and biochemical analysis. *Invest Ophthalmol Vis Sci* 27: 153–163
- Wiechmann AF, Hollyfield JG (1988) HIOMT-like immunoreactivity in the vertebrate retina: A species comparison. *Exp Eye Res* 49: 1079–1095
- Wiechmann AF, Wirsig-Wiechmann CR (1991) Localization and quantification of high-affinity melatonin binding sites in *Rana pipiens* retina. *J Pineal Res* 10: 174–179
- Wiechmann AF, Wirsig-Wiechmann CR (1994) Melatonin receptor distribution in the brain and retina of a lizard, *Anolis carolinensis*. *Brain Behav Evol* 43: 26–33

(Received April 16, 1997 / Accepted May 14, 1997)