



Distribution and Function of Gonadotropin-Releasing Hormone (GnRH) in the Teleost Brain

Authors: Amano, Masafumi, Urano, Akihisa, and Aida, Katsumi

Source: Zoological Science, 14(1) : 1-11

Published By: Zoological Society of Japan

URL: <https://doi.org/10.2108/zsj.14.1>

BioOne Complete (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.

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.

[REVIEW]

Distribution and Function of Gonadotropin-Releasing Hormone (GnRH) in the Teleost Brain

Masafumi Amano^{1*}, Akihisa Urano² and Katsumi Aida³

¹*Nikko Branch, National Research Institute of Aquaculture, Nikko, Tochigi 321-16, Japan*

²*Division of Biological Sciences, Hokkaido University, Sapporo, Hokkaido 060, Japan*

³*Department of Aquatic Bioscience, Graduate School of Agricultural and Life Sciences, The University of Tokyo, Bunkyo-ku, Tokyo 113, Japan*

INTRODUCTION

Gonadotropin-releasing hormone (GnRH) is a decapeptide originally isolated from pig and sheep hypothalamus as a physiologic regulator of luteinizing hormone (LH) release from the pituitary (Matsuo *et al.*, 1971; Burgas *et al.*, 1972). At present, nine GnRH molecules have been characterized and named for the vertebrate species in which they were first identified (Fig. 1): mammalian GnRH, chicken GnRH-I (King and Millar, 1982a,b; Miyamoto *et al.*, 1982, 1983), chicken GnRH-II (Miyamoto *et al.*, 1984), salmon GnRH (Sherwood *et al.*, 1983), lamprey GnRH-I (Sherwood *et al.*, 1986), lamprey GnRH-III (Sower *et al.*, 1993), catfish GnRH (Bogerd *et al.*, 1992; Ngamvongchon *et al.*, 1992), dogfish GnRH (Lovejoy *et al.*, 1992), and seabream GnRH (Powell *et al.*, 1994). They have been identified in vertebrate brains and constitute a family of structurally-related decapeptides. During the 500 million years of vertebrate evolution, the primary structure of GnRH has been remarkably conserved.

It is generally accepted that GnRH regulates synthesis and release of pituitary gonadotropin (GTH) (see King and Millar, 1992; Sherwood *et al.*, 1993). In addition, GnRH can act as a neuromodulator, and administration of exogenous GnRH facilitates sexual behavior in many species (see Pfaff *et al.*, 1987).

In mammalian, avian, reptilian, and amphibian animals, GnRH is conveyed to the pituitary via the hypothalamo-hypophyseal portal vessels. In mammals, pulsatile release of mammalian GnRH (mGnRH) by hypothalamic neurons stimulates GTH secretion from the pituitary. Teleost fishes lack the median eminence. Instead GnRH neurons are found to directly innervate the pituitary. It is therefore interesting to examine GnRH systems in teleost fish in view of comparative endocrinology.

Immunocytochemistry and radioimmunoassay (RIA) have

been utilized for studying the distribution and function of GnRHs in the brain. In addition, recent progress in molecular biological methods has enabled us to study expression of GnRH genes using hybridization techniques (see Urano and Hyodo, 1990).

This review will focus on the roles of the GnRHs in the teleost brain, particularly in salmonid fishes.

IDENTIFICATION OF GnRH

In teleost fish, the primary structure of salmon GnRH (sGnRH) was first determined from chum salmon, *Oncorhynchus keta* (Sherwood *et al.*, 1983), followed by subsequent determination of catfish GnRH (Ngamvongchon *et al.*, 1992) and seabream GnRH (Powell *et al.*, 1994).

The presence of two types of GnRH, sGnRH and chicken GnRH-II (cGnRH-II), in the teleost brain was first demonstrated in the goldfish, *Carassius auratus*, by employing high performance liquid chromatography (HPLC) in conjunction with RIA (Yu *et al.*, 1988). Recent studies have shown that in teleosts, more than one type of GnRH molecule exist even within the same species, and all of the teleosts examined thus far have cGnRH-II, whereas the second form is either sGnRH, mGnRH, catfish GnRH, or seabream GnRH. Existence of three forms of GnRH, i.e. sGnRH, cGnRH-II, and seabream GnRH, was recently reported in the brain of the seabream, *Sparus aurata* (Powell *et al.*, 1994) and African cichlid, *Haplochromis burtoni* (White *et al.*, 1995). The existence of multiple forms of GnRH in the brain suggests that each GnRH has a different distribution and function.

Differential distribution of multiple forms of GnRH in discrete brain areas was examined by RIA in several fishes in order to clarify their functions in the brain. Okuzawa *et al.* (1990) first measured sGnRH and cGnRH-II contents in the discrete brain regions of the rainbow trout, *Oncorhynchus mykiss*, using specific RIAs. These authors found that the contents of both types of GnRHs varied in different brain regions. The levels of sGnRH were higher than those of

* Corresponding author: Tel. +81-288-55-0055;
FAX. +81-288-55-0064.

	1	2	3	4	5	6	7	8	9	10	
Mammalian	p	Glu	-His	-Trp	-Ser	-Tyr	-Gly	-Leu	-Arg	-Pro	-Gly-NH ₂
Chicken-I	p	Glu	-His	-Trp	-Ser	-Tyr	-Gly	-Leu	-Gln	-Pro	-Gly-NH ₂
Chicken-II	p	Glu	-His	-Trp	-Ser	-His	-Gly	-Trp	-Tyr	-Pro	-Gly-NH ₂
Salmon	p	Glu	-His	-Trp	-Ser	-Tyr	-Gly	-Trp	-Leu	-Pro	-Gly-NH ₂
Catfish	p	Glu	-His	-Trp	-Ser	-His	-Gly	-Leu	-Gln	-Pro	-Gly-NH ₂
Seabream	p	Glu	-His	-Trp	-Ser	-Tyr	-Gly	-Leu	-Ser	-Pro	-Gly-NH ₂
Dogfish	p	Glu	-His	-Trp	-Ser	-His	-Gly	-Trp	-Leu	-Pro	-Gly-NH ₂
Lamprey-I	p	Glu	-His	-Tyr	-Ser	-Leu	-Glu	-Trp	-Lys	-Pro	-Gly-NH ₂
Lamprey-III	p	Glu	-His	-Trp	-Ser	-His	-Asp	-Trp	-Lys	-Pro	-Gly-NH ₂

Fig. 1. Amino acid sequences of the identified GnRH peptides in vertebrates.

cGnRH-II in the olfactory bulbs, the telencephalon, the hypothalamus, the optic tectum-thalamus and the pituitary, whereas the cerebellum and the medulla oblongata contained much more cGnRH-II than sGnRH. Especially of note, cGnRH-II was undetectable in the pituitary. This is also true for masu salmon, *Oncorhynchus masou* (Amano *et al.*, 1992, 1993). These results suggest that, of the two GnRHs, only sGnRH is involved in GTH secretion. As an example, sGnRH contents and cGnRH-II contents in each region of the brain of ovulated female masu salmon are shown in Fig. 2.

In the goldfish, sGnRH was distributed in a larger amount in the olfactory bulbs, the telencephalon, the hypothalamus, and the pituitary than in the other regions, whereas cGnRH-II was distributed widely throughout the brain with highest concentrations in the medulla oblongata. The major difference

between salmonid fishes and goldfish is that goldfish pituitary contains cGnRH-II (Kobayashi *et al.*, 1992, 1994).

In the European eel, *Anguilla anguilla*, mGnRH levels were higher than cGnRH-II levels in the pituitary, the olfactory lobes together with the telencephalon, and the diencephalon together with the mesencephalon, while the opposite results were obtained for the posterior part of the brain. Of interest, cGnRH-II levels in the pituitary were slightly above the detectable limit (Dufour *et al.*, 1993).

These studies demonstrated that sGnRH (or mGnRH) and cGnRH-II are differently distributed in the brain, and also necessitated to investigate the localization of GnRH neurons and the changes in GnRH levels during gonadal maturation.

IMMUNOCYTOCHEMICAL DISTRIBUTION OF GnRH NEURONS

There have been many immunocytochemical studies relating to the GnRH system in teleost brains. Serious problems here are that most of these studies used antiserum against mGnRH, for example, in the rainbow trout (Goos and Murathanoglu, 1977; Schäfer *et al.*, 1989), in the goldfish (Stell *et al.*, 1984; Kah *et al.*, 1984), in the platyfish, *Xiphophorus maculatus* (Münz *et al.*, 1981; Halpern-Sebold and Schreiberman, 1983), in the eel (Nozaki *et al.*, 1985; Grober *et al.*, 1987), in the catfish, *Clarias batrachus* (Subheader and Krishna, 1988), in the labrid fish (Grober and Bass, 1991). Some researchers used antiserum against sGnRH, without any characterization of cross reactivity to cGnRH-II, i.e., in the goldfish (Kah *et al.*, 1986), in the green molly, *Poecilia latipinna* (Batten *et al.*, 1990), and in the rainbow trout (Baillache *et al.*, 1994). Since, as is mentioned above, more than one type of GnRH molecule exists even within the same species, several authors have immunocytochemically examined the distribution of multiple GnRH forms in the teleost fish brains (Amano *et al.*, 1991; Montero *et al.*, 1994; Yamamoto *et al.*, 1995; Kim *et al.*, 1995).

The distribution of sGnRH immunoreactive (ir) neuronal somata and fibers, and that of cGnRH-II-ir neuronal somata

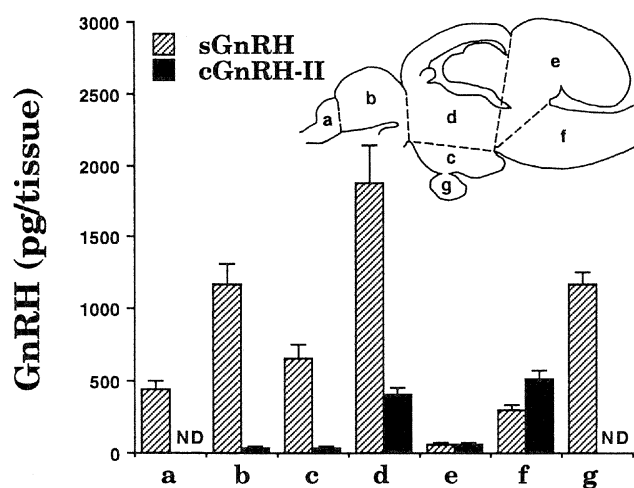


Fig. 2. Contents of sGnRH and cGnRH-II per brain region in ovulated female masu salmon. Schematic diagram of a sagittal section of masu salmon brain shows dissection for the determination of GnRH. Letters represent the following brain areas: a, olfactory bulbs; b, telencephalon including the POA; c, medio-basal hypothalamus; d, optic tectum-thalamus and dorsal hypothalamus; e, cerebellum; f, medulla oblongata; g, pituitary.

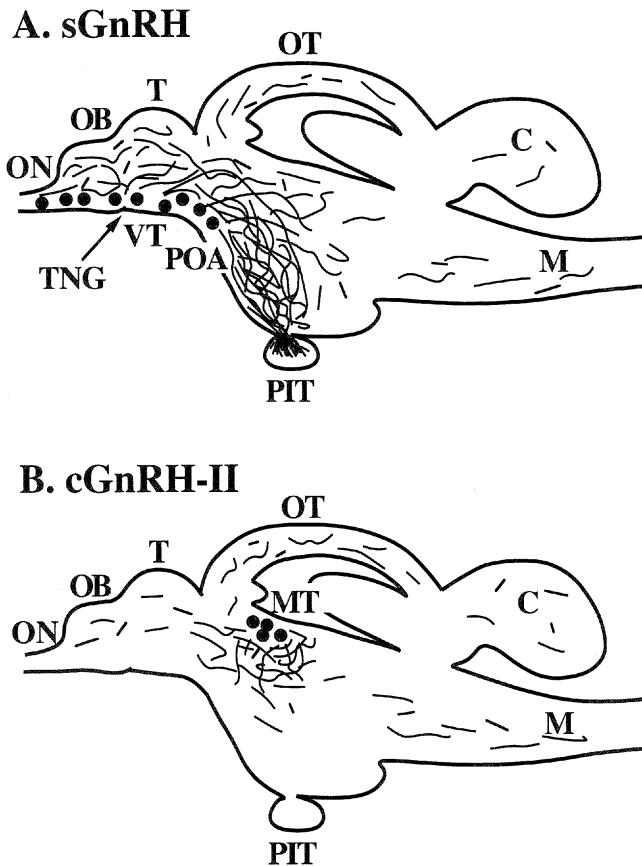


Fig. 3. Schematic illustration of the distribution of (A) sGnRH-ir neuronal somata (filled circles) and fibers, and (B) cGnRH-II-ir neuronal somata (filled circles) and fibers in masu salmon. ON, olfactory nerve; OB, olfactory bulb; TNG, terminal nerve ganglion; T, telencephalon; VT, ventral telencephalon; POA, preoptic area; OT, optic tectum-thalamus; PIT, pituitary; MT, midbrain tegmentum; C, cerebellum; M, medulla oblongata.

and fibers in the masu salmon, are summarized in Fig. 3 (Amano *et al.*, 1991). sGnRH-ir neuronal somata were scattered in the olfactory nerve (ON), the olfactory bulb (OB), between the olfactory bulb and the part of telencephalon which corresponds to the terminal nerve ganglion (TNG), the ventral telencephalon (VT), and the preoptic area (POA). sGnRH-ir fibers were distributed in various brain regions from the OB to the spinal cord. sGnRH-ir fibers directly innervated the pituitary. cGnRH-II-ir neuronal somata were found in the midbrain tegmentum located rostral to the motoneurons of the oculomotor nerve. The distribution of cGnRH-II-ir fibers was basically similar to that of sGnRH-ir fibers except for the absence of cGnRH-II-ir fibers in the pituitary. The number of cGnRH-II-ir fibers in the brain were much fewer than those of sGnRH. The distribution of sGnRH-ir neuronal somata in chum salmon was consistent with that in masu salmon (Kudo *et al.*, 1996). These results suggest that, in salmonid, sGnRH not only regulates GTH secretion but also functions as a neuromodulator, whereas cGnRH-II functions only as a neuromodulator. Nonetheless, both GnRHs can stimulate release of GTH I and GTH II from the pituitary *in vitro* in sockeye

salmon, *Oncorhynchus nerka* (Amano, 1993).

Differential localization of two types of GnRH, mGnRH and cGnRH-II, were reported in the European silver eel (Montero *et al.*, 1994). mGnRH-ir neuronal somata were observed in the OB, the nucleus olfactoryretinalis, the VT, the POA, and the mediobasal hypothalamus. mGnRH-ir fibers were distributed in many parts of the brain and also in the pituitary. cGnRH-II-ir neuronal somata were detected in the midbrain tegmentum, and very few cGnRH-II-ir fibers were observed in the pituitary.

In the goldfish, sGnRH-ir neuronal somata were localized in the TNG area between the ON and the OB, the VT, the POA, and the hypothalamus. cGnRH-II-ir neuronal somata were observed in the TNG, the VT, the POA, the hypothalamus and the midbrain tegmentum. Both sGnRH-ir and cGnRH-II-ir fibers were distributed not only in the hypothalamus and the pituitary but also in various brain areas from the OB to the spinal cord (Kim *et al.*, 1995). These results suggest that both sGnRH and cGnRH-II not only regulates GTH secretion but also function as neuromodulators. Indeed, both forms of GnRH have been shown to induce *in vitro* release of GTH II and growth hormone (GH) in goldfish (Marchant and Peter, 1989; Marchant *et al.*, 1989; Chang *et al.*, 1990; Habibi *et al.*, 1992). Although both GnRHs bind to the same pituitary receptors (Habibi, 1991; Habibi *et al.*, 1992), they appear to induce hormone release via somewhat dissimilar mechanisms (Chang *et al.*, 1991, 1992). Moreover, stimulation of sGnRH and cGnRH-II on GTH II synthesis was shown in goldfish (Khakoo *et al.*, 1994); sGnRH, but not cGnRH-II, increased the accumulation of GTH II β and GTH α mRNA in sexually regressed fish, whereas both sGnRH and cGnRH-II stimulated accumulation of GTH II β and GTH α mRNA in sexually mature fish.

An approach requisite for clarification of the function of each GnRH-ir neuronal group is to examine its projection area in the brain. Recently, three different projection patterns were demonstrated in dwarf gourami, *Colisa laria*. GnRH neurons in the TNG which showed strong sGnRH and weaker cGnRH-II immunoreactivity projected to wide areas of the central nervous system from the OB to the spinal cord; sGnRH neurons in the POA projected only to the pituitary, and cGnRH-II neurons in the midbrain tegmentum projected mainly to brain regions posterior to the hypothalamus and the spinal cord (Yamamoto *et al.*, 1995). These different projection patterns indicate functional differentiation of GnRH neuronal groups.

CHANGES IN GnRH CONTENTS DURING GONADAL MATURATION

If GnRH is involved in gonadal maturation, GnRH contents would be expected to change during gonadal maturation. Several studies were conducted to measure brain GnRH contents by RIA in relation to gonadal maturation in eel (Dufour *et al.*, 1982), platyfish (Schreibman *et al.*, 1983), brown trout, *Salmo trutta* (Breton *et al.*, 1986), caribe colorado, *Pygocentrus notatus* (Gentile *et al.*, 1986), goldfish (Yu *et al.*, 1987), and

chinook salmon, *Oncorhynchus tshawytsca* (Lewis *et al.*, 1992). However, the results were discordant. A clear correlation between brain GnRH contents and gonadal maturity was observed only in caribe colorado (Gentile *et al.*, 1986). Such discrepancies may be, in part, due to the use of RIAs employing nonspecific antibodies.

We investigated changes in sGnRH and cGnRH-II contents in the brain and pituitary of masu salmon from hatching through gonadal maturation for three years. During gonadal maturation, sGnRH levels in the telencephalon including the POA and the pituitary correlatively increased with the elevation in GTH II levels in the pituitary and the plasma (Fig. 4). cGnRH-II were undetectable in the pituitary. Further, no significant changes in the concentration were found in discrete brain areas during vitellogenesis and ovulation (Amano *et al.*, 1992). These results together with those of immunocytochemical studies suggest that sGnRH neurons in the telencephalon-POA are involved in gonadal maturation in masu salmon.

Recently, it was demonstrated that GnRH fibers originating from the TNG is not involved in GTH secretion and further in gonadal maturation in goldfish. The sGnRH contents in the brain except the OB markedly decreased by olfactory tract sectioning (OTX), whereas the cGnRH-II contents in the brain showed no clear changes. Despite large decreases in the brain sGnRH contents, gonadal maturation was not inhibited (Kobayashi *et al.*, 1992, 1994). In dwarf gourami, GnRH neurons in the TNG, possibly sGnRH neurons, may be the most extensively projecting GnRH neurons in the brain except in the pituitary (Oka and Matsushima, 1993). These results indicate that most of the sGnRH fibers in the brain originates from the TNG, and that sGnRH neurons in the TNG do not project to the pituitary. Thus, it is possible that changes in the sGnRH contents measured by RIA reflect the activities of GnRH neurons in the TNG. It should be noted again that the levels of GnRH measured by RIA must be considered as a summation of synthesis, release and degradation of GnRH at any point in development. Therefore, it is necessary to examine the expression of GnRH gene in order to clarify function of GnRH in reproduction.

MOLECULAR CLONING OF GnRH GENES

There are several methods for the examination of hormonal gene expression. Among them, *in situ* hybridization (ISH) can be used to analyze mRNA expression of tissues of interest directly on histological sections (see Urano and Hyodo, 1990). Since sGnRH neuronal somata are widely scattered in the brain, ISH in combination with immunocytochemistry is a strong tool to yield information on the dynamic aspects of the synthesis of GnRH in a certain neuron or region. However, the ISH method require a hybridization probe whose nucleotide sequence is complementary to the mRNA to be examined.

The cDNA coding for mGnRH was initially isolated from human placenta (Seeburg and Adelman, 1984), and subsequently, mGnRH genes have been cloned from several

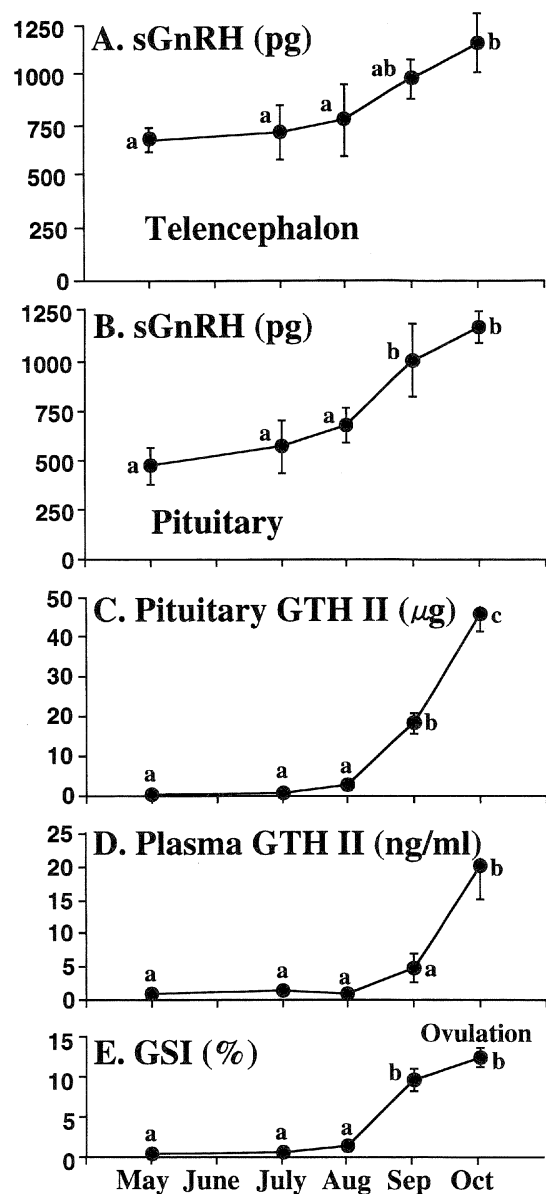


Fig. 4. Changes in (A) sGnRH contents in the telencephalon, (B) sGnRH contents in the pituitary, (C) GTH II contents in the pituitary, (D) GTH II concentrations in the plasma, and (E) gonadosomatic index (GSI) of 2-year-old female masu salmon. Means with differing letters differ significantly ($p < 0.05$) in each panel.

species (Adelman *et al.*, 1986; Mason *et al.*, 1986). Chicken GnRH-I (cGnRH-I) gene has been cloned from chicken (Dunn *et al.*, 1993). The cDNA for cGnRH-II has been isolated from teleost fish (White *et al.*, 1994; Bogerd *et al.*, 1994; Lin and Peter, 1996), the cDNA for sGnRH from several teleost fish (Bond *et al.*, 1991; Suzuki *et al.*, 1992; Klungland *et al.*, 1992; Okuzawa *et al.*, 1994; Grober *et al.*, 1995; Ashihara *et al.*, 1995; Suetake *et al.*, 1995; Lin and Peter, 1996), cDNA for catfish GnRH from African catfish, *Clarias gariepinus* (Bogerd *et al.*, 1994), and cDNA for seabream GnRH from African cichlid, *Haplochromis burtoni* (White *et al.*, 1995) and from red seabream (Okuzawa *et al.*, 1996).

In general, a GnRH precursor is composed of a signal peptide (SP), GnRH and a GnRH-associated peptide (GAP) which is connected to GnRH by a Gly-Lys-Arg sequence. The number of amino acid residues in SP and GAP in teleost GnRH precursors are shown in Table 1. The Gly-Lys-Arg sequence is considered to serve as a signal for proteolytic processing and C-terminal amidation (Nikolics *et al.*, 1988). It was reported that GAP showed GTH-releasing activity and prolactin-inhibiting activity in rat (Nikolics *et al.*, 1985), although prolactin-inhibiting activity of GAP is controversial. There have been no reports on the physiological functions of GAP in teleost fishes.

The distribution of GnRH ISH positive neurons has been examined in several teleost fishes (Suzuki *et al.*, 1992; Bailhache *et al.*, 1994; White *et al.*, 1995; Bogerd *et al.*, 1994). The distribution of sGnRH ISH positive neurons is consistent with that of sGnRH-ir neuronal somata in masu salmon (Suzuki *et al.*, 1992), rainbow trout and Atlantic salmon (Bailhache *et al.*, 1994). In African catfish, catfish GnRH ISH positive neurons were scattered in the ON, along both sides of the midline of the telencephalon, the POA, and in the infundibular stalk close to the pituitary, whereas cGnRH-II ISH positive neurons were observed in the midbrain tegmentum (Bogerd *et al.*, 1994). In African cichlid, sGnRH ISH positive neurons were detected in the TNG, whereas seabream GnRH ISH positive neurons were detected in the POA, and cGnRH-II ISH positive neurons were detected in the mesencephalon (White *et al.*, 1995). In red seabream, sGnRH ISH positive neurons were detected in the TNG, and seabream GnRH ISH neurons were detected in the POA (Okuzawa *et al.*, 1996). All these studies support the data obtained from immunocytochemistry.

REGULATION OF sGnRH mRNA EXPRESSION IN SALMONID FISHES

The cDNA sequences for sGnRH, which is involved in gonadal maturation through GTH secretion, have been isolated

from several salmonid fishes (masu salmon, Suzuki *et al.*, 1992; Atlantic salmon, Klungland *et al.*, 1992; sockeye salmon, Ashihara *et al.*, 1995), making it possible to examine sGnRH synthetic activity using ISH. Hence, we examined the changes of sGnRH mRNA expression in context of several aspects of reproduction in salmonid fish.

(a) Changes in sGnRH mRNA expression during gonadal maturation

The widespread distribution of sGnRH-ir neuronal somata in the ventral part of the brain suggests that sGnRH has several functions in the brain in addition to the stimulation of GTH secretion (Amano *et al.*, 1991); however, it still remains obscure which sGnRH neurons are involved in gonadal maturation via GTH secretion. We therefore examined the changes of sGnRH mRNA expression during ovulation in 2-year-old female masu salmon (Amano *et al.*, 1995a). In this study, sGnRH synthetic activity were estimated by the number of neurons expressing sGnRH mRNA, the number of silver grains per neuron, and the total number of silver grains per unit area. The activity was increased in the VT and the POA during maturation in accordance with increases in GSI and plasma GTH II concentrations (Fig. 5). On the contrary, no significant changes were observed in the OB and the TNG. These results indicate that sGnRH neurons in the VT and the POA, but not in the OB and the TNG, are involved in the regulation of gonadal maturation possibly through GTH secretion. These results are consistent with the previous data that sGnRH concentrations in the telencephalon including the POA increased with gonadal maturation (Amano *et al.*, 1992, 1993).

In the dwarf gourami, GnRH originating from the TNG does not affect GTH secretion but rather has a function as a neuromodulator in the brain (Oka and Ichikawa, 1990; Oka, 1992; Yamamoto *et al.*, 1995). sGnRH originating from the TNG is also not considered to be essential for gonadal development in goldfish (Kobayashi *et al.*, 1992, 1994). It is

Table 1. Amino acid numbers of signal peptide (SP) and GnRH associated peptide (GAP) of GnRH precursors identified in teleost fishes

GnRH form	Species	SP	GAP	References
sGnRH	cichlid	23	54	Bond <i>et al.</i> (1991)
	masu salmon	23	46	Suzuki <i>et al.</i> (1992)
	Atlantic salmon	23	46	Klungland <i>et al.</i> (1992)
	red seabream	23	54	Okuzawa <i>et al.</i> (1994)
	sockeye salmon	23	46	Ashihara <i>et al.</i> (1995)
	plainfin midshipman	23	53	Grober <i>et al.</i> (1995)
	goldfish	23	58	Suetake <i>et al.</i> (1995)
	goldfish	23	58	Lin and Peter (1996)
cGnRH-II	cichlid	23	49	White <i>et al.</i> (1994)
	catfish	24	49	Bogerd <i>et al.</i> (1994)
	goldfish	24	49	Lin and Peter (1996)
catfish GnRH	catfish	21	46	Bogerd <i>et al.</i> (1994)
seabream GnRH	cichlid	22	63	Bogerd <i>et al.</i> (1995)
	red seabream	23	59	Okuzawa <i>et al.</i> (1996)

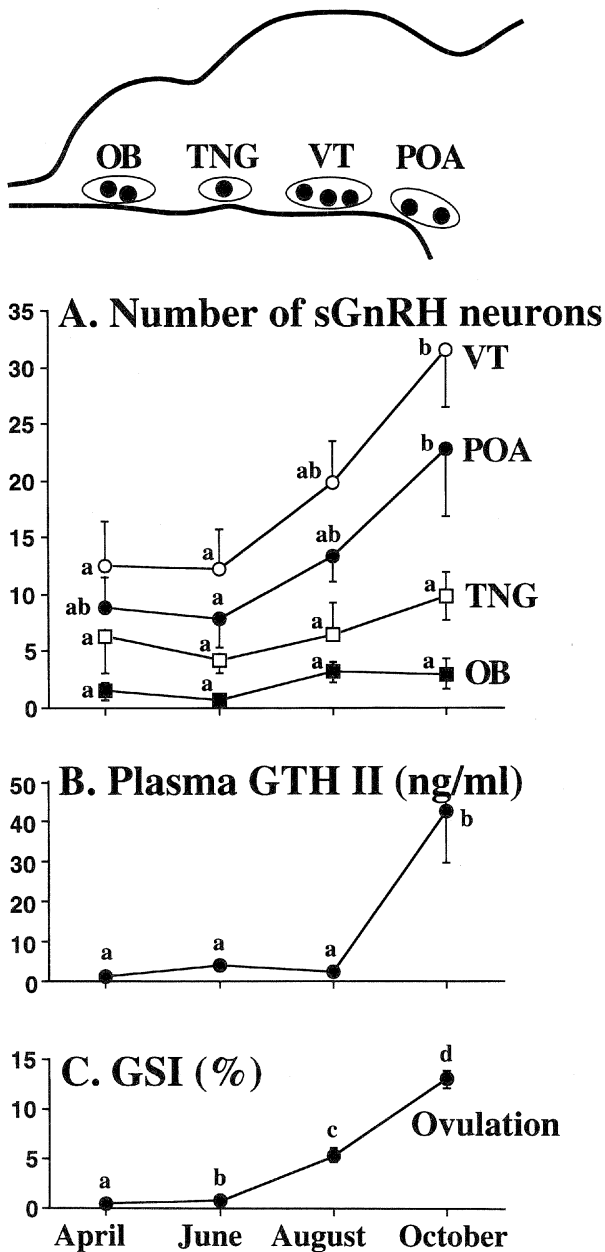


Fig. 5. Changes in (A) the number of neurons expressing sGnRH mRNA in the brain (OB, TNG, VT, POA), (B) plasma GTH II concentrations, and (C) GSI of 2-year-old female masu salmon. Means with differing letters differ significantly ($p < 0.05$) in each panel.

also possible that sGnRH neurons in the TNG function to only modulate neuronal activity in masu salmon.

(b) Changes in sGnRH mRNA expression induced by photoperiod manipulation

Gonadal maturation in salmonid fish occurs in autumn, since the decreasing photoperiod in autumn accelerates gonadal maturation (Billard *et al.*, 1978). Testicular maturation of underyearling precocious male masu salmon could be experimentally manipulated by changing the length of the light-

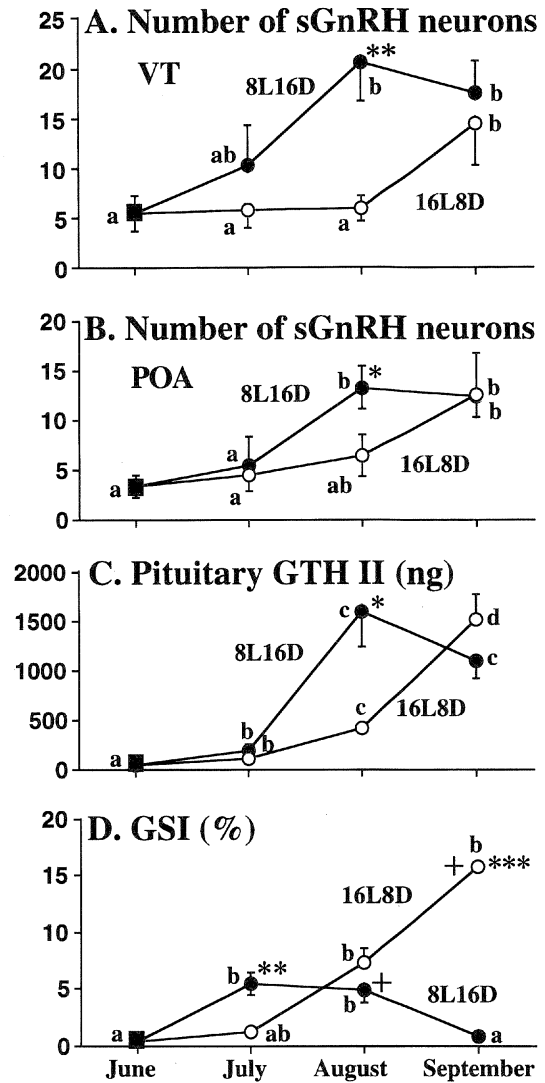


Fig. 6. Changes in (A) the number of neurons expressing sGnRH mRNA in the VT, (B) the number of neurons expressing sGnRH mRNA in the POA, (C) pituitary GTH II contents, and (D) GSI of underyearling male masu salmon reared under 8L16D or 16L8D. * $p < 0.05$; ** $p < 0.01$; between the 8L16D and 16L8D group in each month. Means with differing letters differ significantly ($p < 0.05$) in each panel.

dark photoperiod. Maturation was accelerated by changing the photoperiod from natural to short (8L16D) in June, and was delayed by keeping the photoperiod long (16L8D) from June (Amano *et al.*, 1994a). sGnRH mRNA levels in the VT and the POA increased when the fish spermiated; the activity increased in August in the 8L16D group, and in September in the 16L8D group, respectively. Moreover, the increase of sGnRH mRNA levels was in accordance with the increase of pituitary GTH II contents (Fig. 6). No significant changes in sGnRH mRNA levels in relation to gonadal maturation were observed in the OB and the TNG (Amano *et al.*, 1995b). These results indicate that sGnRH neurons in the VT and the POA are influenced by photoperiod, and are involved in the

regulation of gonadal maturation through GTH secretion.

(c) Changes in sGnRH mRNA expression induced by sex steroids

Accumulation of GTH in the pituitary can be stimulated by aromatizable androgen or estrogen in juvenile fish; this is a known positive feedback system (see Goos, 1987). The involvement of GnRH in this mechanism is speculated, because sex steroid administration increased the amount of GnRH in the hypothalamus of the European silver eel (Dufour *et al.*, 1985), and rainbow trout (Goos *et al.*, 1986). On the other hand, the stimulatory effects of testosterone on the expression of pituitary GTH II β gene was demonstrated *in vitro* in juvenile rainbow trout (Xiong *et al.*, 1993). Thus, whether steroids have direct actions on the pituitary, or act indirectly via GnRH was unclear.

We examined the effects of 17 α -methyltestosterone (MT) on sGnRH mRNA expression in yearling masu salmon (Amano *et al.*, 1994b). Oral MT application markedly increased pituitary GTH II β , but not GTH I β concentrations in both sexes. In future precocious males, MT treatment further increased the number of neurons expressing sGnRH mRNA in the POA but not in the OB and the VT (Fig. 7), whereas sGnRH mRNA levels were not changed by MT in immature females. These results suggest that sGnRH is involved in the positive feedback system at least in future precocious males, and that the difference in the responsiveness of preoptic sGnRH neurons to MT is based on the maturational stage of the fish. The result that sGnRH mRNA levels in the POA was increased by the administration of MT in 2-year-old females which are just before the initiation of gonadal maturation supports this hypothesis (Amano *et al.*, 1997). Of note, studies on pubertal development have been conducted in a number of teleost fish species such as the rainbow trout (Gielen *et al.*, 1982; Goos *et al.*, 1986), the eel (Dufour *et al.*, 1985; Counis *et al.*, 1987), the platyfish (Schreibman *et al.*, 1986), and African catfish (Schulz *et al.*, 1994a,b). These studies suggest that sex steroids initiate and/or accelerate the development of the brain-pituitary-gonadal axis. Taken together, the response of preoptic sGnRH neurons to steroids is a necessary condition for gonadal maturation or the development of the brain-pituitary-gonadal axis.

(d) Changes in sGnRH mRNA expression during seaward migration

sGnRH neurons in the ON and the OB may be involved in the seaward migration of salmonid fish, as the importance of olfactory functions during homing migration has been confirmed. Interestingly, sGnRH mRNA expression in cribriform ganglion in the ON increased during downstream migration in juvenile chum salmon (Parhar *et al.*, 1994). Meanwhile, changes of sGnRH-producing neurons in chum salmon during homing migration from coastal seas to the spawning ground of the maternal river was examined using ISH (Kudo *et al.*, 1996). sGnRH mRNA levels in the ON and the ON-OB were high in fish in the coastal seas, but activity decreased in the spawning ground. These results suggest that

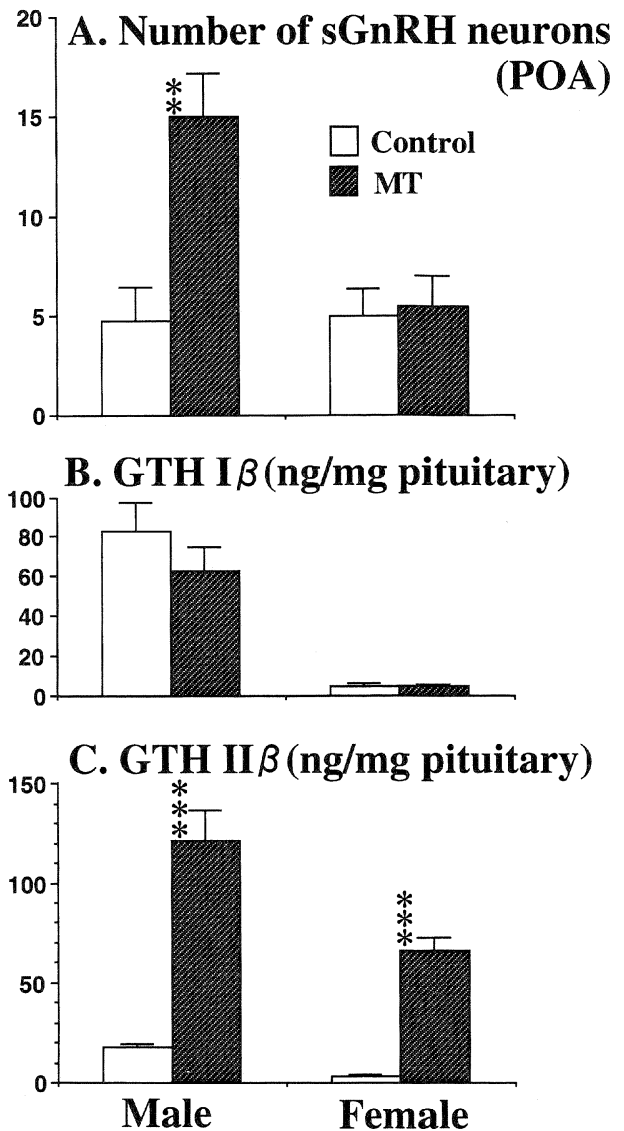


Fig. 7. Changes in (A) the number of neurons expressing sGnRH mRNA in the POA, (B) pituitary GTH I β concentrations, and (C) pituitary GTH II β concentrations in the control and the MT-treated groups. **($P < 0.01$) and ***($p < 0.001$) indicate the level of significant difference between the control and the MT-treated groups.

sGnRH neurons in the ON and probably some in the ON-OB may be involved in seaward migration.

(e) Existence of two differing precursor genes for sGnRH

Existence of two different genes for sGnRH have been demonstrated in sockeye salmon (Ashihara *et al.*, 1995). These authors found two different cDNAs for sGnRH precursors (pro sGnRH-I and pro sGnRH-II); pro sGnRH-I cDNA is 436 base pair long (short type) and pro sGnRH-II cDNA is 482 base pair long (long type). A question arising here is whether the two genes encoding sGnRH are expressed equally or differently. We are now attempting to examine the distribution of sGnRH neurons expressing short type and/or long type

sGnRH precursors in the sockeye salmon brain using ISH.

CONCLUSION

At present, nine GnRH molecules have been characterized throughout the vertebrates, and the existence of multiple forms of GnRH in the brain was observed also in teleost fish. All of the teleosts examined thus far have cGnRH-II, whereas the second form is either sGnRH, mGnRH, catfish GnRH, or seabream GnRH. Distribution of GnRH neurons was examined using immunocytochemistry. In general, sGnRH neurons were distributed from the ON to the POA or the hypothalamus, whereas cGnRH-II neurons were detected in the midbrain tegmentum. GnRH-ir fibers were distributed in various brain regions, indicating multiple neuroendocrine functions in the brain.

The brain GnRH contents were measured by RIA and related to gonadal maturation, although results are discordant. It was demonstrated that most of the sGnRH fibers in the brain originate from the TNG, and that sGnRH derived from the TNG is not essential for gonadal maturation.

Recent determination of the cDNA encoding GnRH precursors has enabled the investigation of GnRH synthetic activity using ISH. The distribution of GnRH ISH positive neurons was examined in several teleost fishes and the results corresponded to those obtained by immunocytochemical investigation. We examined sGnRH mRNA expression of salmonid fishes, and found that sGnRH neurons in the different brain regions have different functions according to their location.

The function of sGnRH in the brain of teleost fish, especially in salmonids, has been partly elucidated by use of RIA, immunocytochemistry and ISH. However, the function of cGnRH-II, which is distributed in almost all of the teleost fishes examined so far, remains unclear, except for the stimulation of GTH and GH release *in vitro*.

It has been proposed that GnRH-ir neurons are derived from the olfactory placode and migrate to the forebrain during prenatal development in the mouse (mGnRH; Schwanzel-Fukuda and Pfaff, 1989; Wray *et al.*, 1989), the chicken (probably cGnRH-I, Murakami *et al.*, 1991), and the newt, *Cynops pyrrhogaster* (probably mGnRH, Murakami *et al.*, 1992). In chum salmon and sockeye salmon, GnRH (probably sGnRH) neurons originate in the olfactory placode and then migrate into the brain along the ON (Chiba *et al.*, 1994; Parhar *et al.*, 1995). Recently, it has been reported that cGnRH-II are not olfactory placode origin in the axolotl, *Ambystoma mexicanum* (Northcutt and Muske, 1994). cGnRH-II may not originate from the olfactory placode in teleost fish as well. Studies on the ontogeny of the GnRH system may be helpful in understanding the function of GnRH in the brain.

ACKNOWLEDGMENTS

Our research cited in this review was obtained at the Department of Aquatic Bioscience, Graduate School of Agricultural and Life Sciences, The University of Tokyo, and the Nikko Branch of the National Research Institute of Aquaculture. It was supported in part by grants from the Ministry of Education, Culture and Science, and the Fisheries Agency, Japan. We thank Professor Emeritus Seiichiro Kawashima and Associate Professor Yoshitaka Oka, The University of Tokyo, for instruction in immunocytochemistry. We are indebted to Dr. Susumu Hyodo, The University of Tokyo, for giving us the opportunity to study *in situ* hybridization. We are also thankful to Professor Yoshihisa Hasegawa and Professor Hiroshi Kawauchi, Kitasato University, for providing us the antisera against cGnRH-II and GTH (GTH I β and GTH II β). We also thank Dr. Marcy N. Wilder, Japan International Research Center for Agricultural Sciences, for reading the manuscript.

REFERENCES

- Adelman JP, Mason AJ, Hayflick JS, Seeburg PH (1986) Isolation of the gene and hypothalamic cDNA for the common precursor of gonadotropin-releasing hormone and prolactin release-inhibiting factor in human and rat. *Proc Natl Acad Sci USA* 83:179–183
- Amano M, Oka Y, Aida K, Okumoto N, Kawashima S, Hasegawa Y (1991) Immunocytochemical demonstration of salmon GnRH and chicken GnRH-II in the brain of masu salmon, *Oncorhynchus masou*. *J Comp Neurol* 314:587–597
- Amano M, Aida K, Okumoto N, Hasegawa Y (1992) Changes in salmon GnRH and chicken GnRH-II contents in the brain and pituitary, and GTH contents in the pituitary in female masu salmon, *Oncorhynchus masou*, from hatching through ovulation. *Zool Sci* 9: 375–386
- Amano M, Aida K, Okumoto N, Hasegawa Y (1993) Changes in levels of GnRH in the brain and pituitary and GTH in the pituitary in male masu salmon, *Oncorhynchus masou*, from hatching to maturation. *Fish Physiol Biochem* 11: 233–240
- Amano M (1993) GnRH profiles during the life cycle of salmonid fishes. Thesis Dr Agric, Univ of Tokyo, pp 1–45
- Amano M, Okumoto N, Kitamura S, Ikuta K, Suzuki Y, Aida K (1994a) Salmon gonadotropin-releasing hormone and gonadotropin are involved in precocious maturation induced by photoperiod manipulation in underyearling male masu salmon, *Oncorhynchus masou*. *Gen Comp Endocrinol* 95: 368–373
- Amano M, Hyodo S, Urano A, Okumoto N, Kitamura S, Ikuta K, Suzuki Y, Aida K (1994b) Activation of salmon gonadotropin-releasing hormone synthesis by 17 α -methyltestosterone administration in yearling masu salmon, *Oncorhynchus masou*. *Gen Comp Endocrinol* 95: 374–380
- Amano M, Hyodo S, Kitamura S, Ikuta K, Suzuki Y, Urano A, Aida K (1995a) Salmon GnRH synthesis in the preoptic area and the ventral telencephalon is activated during gonadal maturation in female masu salmon. *Gen Comp Endocrinol* 99: 13–21
- Amano M, Hyodo S, Kitamura S, Ikuta K, Suzuki Y, Urano A, Aida K (1995b) Short photoperiod accelerates preoptic and ventral telencephalic salmon GnRH synthesis and precocious maturation in underyearling male masu salmon. *Gen Comp Endocrinol* 99: 22–27
- Amano M, Ikuta K, Kitamura S, Aida K (1997) The maturation of the salmon GnRH system and its regulation by gonadal steroids in masu salmon. *Fish Physiol Biochem*, in press
- Ashihara M, Suzuki M, Kubokawa K, Kobayashi M, Yoshiura Y, Urano A, Aida K (1995) Two differing precursor genes for the salmon-type gonadotropin-releasing hormone exist in salmonids. *J Mol Endocrinol* 15: 1–9
- Bailhache T, Arazam A, Klungland H, Aleström P, Breton B, Jégo P

- (1994) Localization of salmon gonadotropin-releasing hormone mRNA and peptide in the brain of Atlantic salmon and rainbow trout. *J Comp Neurol* 347: 444–454
- Batten TFC, Cambre ML, Moons L, Vandesande F (1990) Comparative distribution of neuropeptide-immunoreactive systems in the brain of the green molly, *Poecilia latipinna*. *J Comp Neurol* 302: 893–919
- Billard R, Breton B, Fostier A, Jalabert B, Weil C (1978) Endocrine control of the teleost reproductive cycle and its relation to external factors: salmonid and cyprinid models. In "Comparative Endocrinology" Ed by PJ Gaillard, HH Boer, Elsevier, North Holland Biomedical Press, Amsterdam, pp 37–48
- Bogerd J, Li KW, Janssen-Dommerholt C, Goos HJTh (1992) Two gonadotropin-releasing hormones from African catfish (*Clarias gariepinus*). *Biochem Biophys Res Commun* 187: 127–134
- Bogerd J, Zandbergen T, Andersson E, Goos H (1994) Isolation, characterization and expression of cDNAs encoding the catfish-type and chicken-II-type gonadotropin-releasing hormone precursors in the African catfish. *Eur J Biochem* 222: 541–549
- Bond CT, Francis RC, Fernald RD, Adelman JP (1991) Characterization of complementary DNA encoding the precursor for gonadotropin-releasing hormone and its associated peptide from a teleost fish. *Mol Endocrinol* 5: 931–937
- Breton B, Motin A, Billard R, Kah O, Geoffre S, Precigoux G (1986) Immunoreactive gonadotropin-releasing hormone-like material in the brain and pituitary gland during the periovulatory period in the brown trout (*Salmo trutta* L): relationships with the plasma and pituitary gonadotropin. *Gen Comp Endocrinol* 61: 109–119
- Burgas R, Butcher M, Amoss M, Ling N, Monahan M, River J, Fellows R, Blackwell R, Vale W, Guillemin R (1972) Primary structure of the ovine hypothalamic luteinizing hormone-releasing factor (LRF). *Proc Natl Acad Sci USA* 69: 278–282
- Chang JP, Cook H, Freedman GL, Wiggs AJ, Somoza GM, de Leeuw R, Peter RE (1990) Use of a pituitary cell dispersion method and primary culture system for the studies of gonadotropin-releasing hormone action in the goldfish, *Carassius auratus*. I. Initial morphological, static, and cell column perfusion studies. *Gen Comp Endocrinol* 77: 256–273
- Chang JP, Wildman B, Van Goor F (1991) Lack of involvement of arachidonic acid metabolism in chicken gonadotropin-releasing hormone II (cGnRH-II) stimulation of gonadotropin secretion in dispersed pituitary cells of goldfish, *Carassius auratus*: Identification of a major difference in salmon GnRH and chicken GnRH-II mechanisms of action. *Mol Cell Endocrinol* 79: 75–83
- Chang JP, Wong OAL, Van Der Kraak G, Van Goor F (1992) Relationship between cyclic AMP-stimulated and native gonadotropin-releasing hormone stimulated gonadotropin release in the goldfish, *Carassius auratus*. *Gen Comp Endocrinol* 86: 359–377
- Chiba A, Oka S, Honma Y (1994) Ontogenic development of gonadotropin-releasing hormone-like immunoreactive neurons in the brain of the chum salmon, *Oncorhynchus keta*. *Neurosci Lett* 178: 51–54
- Counis R, Dufour S, Ribot G, Querat B, Fontaine YA, Jutisz M (1987) Estradiol has inverse effects on pituitary glycoprotein hormone α -subunit messenger ribonucleic acid in the immature European eel and the gonadectomized rat. *Endocrinology* 121: 1178–1184
- Dufour S, Pasqualini C, Kerdelhue B, Fontaine YA (1982) Presence and distribution of radioimmunoassayable LHRH in the European eel, *Anguilla anguilla*. *Neuropeptides* 3: 159–171
- Dufour S, Fontaine YA, Kerdelhue B (1985) Increase in brain and pituitary radioimmunoassayable gonadotropin releasing hormone (GnRH) in the European silver eel treated with sexual steroid or human chorionic gonadotropin. *Neuropeptides* 6: 495–502
- Dufour S, Montero M, Le Belle N, Bassompierre M, King JA, Millar RP, Peter RE, Fontaine YA (1993) Differential distribution and response to experimental sexual maturation of two forms of brain gonadotropin-releasing hormone (GnRH) in the European eel, *Anguilla anguilla*. *Fish Physiol Biochem* 11: 99–106
- Dunn IC, Chen Y, Hook C, Sharp PJ, Sang HM (1993) Characterization of the chicken preprogonadotrophin-releasing hormone-I gene. *J Mol Endocrinol* 11: 19–29
- Gentile F, Lira O, Marcano-de Cotte D (1986) Relationship between brain gonadotropin-releasing hormone (GnRH) and seasonal reproductive cycle of "caribe colorado", *Pygocentrus notatus*. *Gen Comp Endocrinol* 64: 239–245
- Gielen JTh, Goos HJTh, Peute J, Van den Bosch RA, Van Oordt PGWJ (1982) The brain-pituitary-gonadal axis in the rainbow trout, *Salmo gairdneri*: gonadal hormones and the maturation of gonadotropic cells. *Cell Tissue Res* 225: 45–56
- Goos HJTh, Murathanoglu O (1977) Localization of gonadotropin-releasing hormone (GRH) in the forebrain and of the trout (*Salmo gairdneri*). *Cell Tissue Res* 181: 163–168
- Goos HJTh, de Leeuw R, Cook H, van Oordt PGWJ (1986) Gonadotropic hormone-releasing hormone (GnRH) bioactivity in the brain of the immature rainbow trout, *Salmo gairdneri*: the effect of testosterone. *Gen Comp Endocrinol* 64: 80–84
- Goos HJTh (1987) Steroid feedback on gonadotropin secretion. In "Proc Third Int Symp Reprod Physiol Fish" Ed by DR Idler, LW Crim, JM Walsh, Memorial University Press, St John's, pp 16–20
- Grober MS, Bass AH, Burd G, Marchaterre MA, Segil N, Hodgson T (1987) The nervus terminalis ganglion in *Anguilla rostrata*: an immunocytochemical and HRP histochemical analysis. *Brain Res* 436: 148–152
- Grober MS, Bass AH (1991) Neuronal correlates of sex/role change in labrid fishes: LHRH-like immunoreactivity. *Brain Behav Evol* 38: 302–312
- Grober MS, Myers TR, Marchaterre MA, Bass AH, Myers DA (1995) Structure, localization, and molecular phylogeny of a GnRH cDNA from a paracanthopterygian fish, the plainfin midshipman (*Porichthys notatus*). *Gen Comp Endocrinol* 99: 85–99
- Habibi HR (1991) Homologous desensitization of gonadotropin-releasing hormone (GnRH) receptors in the goldfish pituitary: effects of native GnRH peptides and a synthetic GnRH antagonist. *Biol Reprod* 44: 275–283
- Habibi HR, Peter RE, Nahorniak CS, Milton R Cdel, Millar RP (1992) Activity of vertebrate gonadotropin-releasing hormone analogues with variant amino acid residues in positions 5, 7 and 8 in the goldfish pituitary. *Regul Pept* 37: 271–284
- Halpern-Sebold L, Schreibman MP (1983) Ontogeny of centers containing luteinizing hormone-releasing hormone in the brain of platy fish (*Xiphophorus maculatus*) as determined by immunocytochemistry. *Cell Tissue Res* 229: 75–84
- Kah O, Chambolle P, Dubourg P, Dubois MP (1984) Immunocytochemical localization of luteinizing hormone-releasing hormone in the brain of goldfish *Carassius auratus*. *Gen Comp Endocrinol* 53: 107–115
- Kah O, Breton B, Dulka JG, Nunez-Rodriguez J, Peter RE, Corrigan A, Rivier JE, Vale WW (1986) A reinvestigation of the Gn-RH (gonadotropin-releasing hormone) systems in the goldfish brain using antibodies to salmon Gn-RH. *Cell Tissue Res* 244: 327–337
- Khakoo Z, Bhatia A, Gedamu L, Habibi HR (1994) Functional specificity for salmon gonadotropin-releasing hormone (GnRH) and chicken GnRH-II coupled to the gonadotropin release and subunit messenger ribonucleic acid level in the goldfish pituitary. *Endocrinology* 134: 838–847
- Kim M-H, Oka Y, Amano M, Kobayashi M, Okuzawa K, Hasegawa Y, Kawashima S, Suzuki Y, Aida K (1995) Immunocytochemical localization of sGnRH and cGnRH-II in the brain of goldfish, *Carassius auratus*. *J Comp Neurol* 356: 72–82
- King JA, Millar RP (1982a) Structure of chicken hypothalamic luteinizing hormone-releasing hormone. 1. Structural determination on partially purified material. *J Biol Chem* 257:

- 10722–10728
- King JA, Millar RP (1982b) Structure of chicken hypothalamic luteinizing hormone-releasing hormone. 2. Isolation and characterization. *J Biol Chem* 257: 10729–10732
- King JA, Millar RP (1992) Evolution of gonadotropin-releasing hormones. *Trends Endocrinol Metab* 3: 339–346
- Klungland H, Lorens JB, Andersen O, Kisen GO, Alestrom P (1992) The Atlantic salmon prepro-gonadotropin releasing hormone gene and mRNA. *Mol Cell Endocrinol* 84: 167–174
- Kobayashi M, Amano M, Hasegawa Y, Okuzawa K, Aida K (1992) Effects of olfactory tract section on brain GnRH distribution, plasma gonadotropin levels, and gonadal stage in goldfish. *Zool Sci* 9: 765–773
- Kobayashi M, Amano M, Kim M-H, Furukawa K, Hasegawa Y, Aida K (1994) Gonadotropin-releasing hormones of terminal nerve origin are not essential to ovarian development and ovulation in goldfish. *Gen Comp Endocrinol* 95: 192–200
- Kudo H, Hyodo S, Ueda H, Hiroi O, Aida K, Urano A, Yamauchi K (1996) Cytophysiology of gonadotropin-releasing hormone neurons in chum salmon (*Oncorhynchus keta*) forebrain before and after upstream migration. *Cell Tissue Res* 284: 261–267
- Lewis KA, Swanson P, Sower SA (1992) Changes in brain gonadotropin-releasing hormone, pituitary and plasma gonadotropins, and plasma thyroxine during smoltification in chinook salmon (*Oncorhynchus tshawytsca*). *Gen Comp Endocrinol* 87: 461–470
- Lin X-W, Peter RE (1996) Expression of salmon gonadotropin-releasing hormone (GnRH) and chicken GnRH-II precursor messenger ribonucleic acids in the brain and ovary of goldfish. *Gen Comp Endocrinol* 101: 282–296
- Lovejoy DA, Fischer WH, Ngamvongchon S, Craig AG, Nahorniak CS, Peter RE, Rivier JE, Sherwood NM (1992) Distinct sequence of gonadotropin-releasing hormone (GnRH) in dogfish brain provides insight into GnRH evolution. *Proc Natl Acad Sci USA* 89: 6373–6377
- Marchant TA, Peter RE (1989) Hypothalamic peptides influencing growth hormone secretion in the goldfish, *Carassius auratus*. *Fish Physiol Biochem* 7: 133–139
- Marchant TA, Chang JP, Nahorniak CS, Peter RE (1989) Evidence that gonadotropin-releasing hormone also functions as a growth hormone-releasing factor in the goldfish. *Endocrinology* 124: 2509–2518
- Mason AJ, Hayflick JS, Zoeller RT, Young WS III, Philips HS, Nikolics K, Seeburg PH (1986) A deletion truncating the gonadotropin-releasing hormone gene is responsible for hypogonadism in the hpg mouse. *Science* 234: 1366–1371
- Matsuo H, Baba Y, Nair RMG, Arimura A, Schally AV (1971) Structure of the porcine LH- and FSH-releasing hormone. I. the proposed amino acid sequence. *Biochem Biophys Res Commun* 43: 1334–1339
- Miyamoto K, Hasegawa Y, Minegishi T, Nomura M, Takahashi Y, Igarashi M (1982) Isolation and characterization of chicken luteinizing hormone-releasing hormone. *Biochem Biophys Res Commun* 107: 820–827
- Miyamoto K, Hasegawa Y, Igarashi M, Chino N, Sakakibara S, Kangawa K, Matsuo H (1983) Evidence that chicken hypothalamic luteinizing hormone-releasing hormone is (Gln⁸)-LH-RH. *Life Sci* 32: 1341–1347
- Miyamoto K, Hasegawa Y, Nomura M, Igarashi M, Kangawa K, Matsuo H (1984) Identification of the second gonadotropin-releasing hormone in chicken hypothalamus: evidence that gonadotropin secretion is probably controlled by two distinct gonadotropin-releasing hormones in avian species. *Proc Natl Acad Sci USA* 81: 3874–3878
- Montero M, Vidal B, King JA, Tramu G, Vandesande F, Dufour S, Kah O (1994) Immunocytochemical localization of mammalian GnRH (gonadotropin-releasing hormone) and chicken GnRH-II in the brain of the European silver eel (*Anguilla anguilla* L.). *J Chem Neuroanat* 7: 227–241
- Münz H, Stumpf WE, Jennes L (1981) LHRH systems in the brain of platyfish. *Brain Res* 221: 1–13
- Murakami S, Seki T, Wakabayashi K, Arai Y (1991) The ontogeny of luteinizing hormone-releasing hormone (LHRH) producing neurons in the chick embryo: possible evidence for migrating LHRH neurons from the olfactory epithelium expressing a highly polysialylated neural cell adhesion molecule. *Neurosci Res* 12: 421–431
- Murakami S, Kikuyama S, Arai Y (1992) The origin of the luteinizing hormone-releasing hormone (LHRH) neurons in the newts (*Cynops pyrrhogaster*): the effect of olfactory placode ablation. *Cell Tissue Res* 269: 21–27
- Ngamvongchon S, Lovejoy DA, Fischer WH, Craig AG, Nahorniak CS, Peter RE, Rivier JE, Sherwood NM (1992) Primary structure of two forms of gonadotropin-releasing hormone, one distinct and one conserved, from catfish brain. *Mol Cell Neurosci* 3: 17–22
- Nikolics K, Mason AJ, Szönyi É, Ramachandran J, Seeburg PH (1985) A prolactin-inhibiting factor within the precursor for human gonadotropin-releasing hormone. *Nature* 316: 511–517
- Nikolics K, Seeburg PH, Ramachandran J (1988) The biosynthetic precursor of gonadotropin-releasing hormone. In "Frontiers in Neuroendocrinology Vol 10" Ed by L Martini, WF Ganang, Ravan Press, New York, pp 153–166
- Northcutt RG, Muske LE (1994) Multiple embryonic origins of gonadotropin-releasing hormone (GnRH) immunoreactive neurons. *Dev Brain Res* 78: 279–290
- Nozaki M, Fujita I, Saito N, Tsukahara T, Kobayashi H, Ueda K, Oshima K (1985) Distribution of LHRH-like immunoreactivity in the brain of the Japanese eel (*Anguilla japonica*) with special reference to the nervus terminalis. *Zool Sci* 2: 537–547
- Oka Y, Ichikawa M (1990) Gonadotropin-releasing hormone (GnRH) immunoreactive system in the brain of the dwarf gourami (*Colisa lalia*) as revealed by light microscopic immunocytochemistry using a monoclonal antibody to common amino acid sequence of GnRH. *J Comp Neurol* 300: 511–522
- Oka Y (1992) Gonadotropin-releasing hormone (GnRH) cells of the terminal nerve as a model neuromodulator system. *Neurosci Lett* 142: 119–122
- Oka Y, Matsushima T (1993) Gonadotropin-releasing hormone (GnRH)-immunoreactive terminal nerve cells have intrinsic rhythmicity and project widely in the brain. *J Neurosci* 13: 2161–2176
- Okuzawa K, Amano M, Kobayashi M, Aida K, Hanyu I, Hasegawa Y, Miyamoto K (1990) Differences in salmon GnRH and chicken GnRH-II contents in discrete brain areas of male and female rainbow trout according to age and stage of maturity. *Gen Comp Endocrinol* 80: 116–126
- Okuzawa K, Araki K, Tanaka H, Kagawa H, Hirose K (1994) Molecular cloning of a cDNA encoding the prepro-salmon gonadotropin-releasing hormone of the red seabream. *Gen Comp Endocrinol* 96: 234–242
- Okuzawa K, Granneman J, Bogerd J, Goos HJTh, Zohar Y, Kagawa H (1996) Distinct expression of GnRH genes in the red seabream brain. In "Proc Third Int Symp Fish Endocrinol" Hakodate, Japan, [Abstract p 59]
- Parhar IS, Koibuchi N, Sakai M, Iwata M, Yamaoka S (1994) Gonadotropin-releasing hormone (GnRH): expression during salmon migration. *Neurosci Lett* 172: 15–18
- Parhar IS, Iwata M, Pfaff DW, Schwanzel-Fukuda M (1995) Embryonic development of gonadotropin-releasing hormone neurons in the sockeye salmon. *J Comp Neurol* 362: 256–270
- Pfaff DW, Jorgensen K, Kow L-M (1987) Luteinizing-hormone releasing hormone in rat brain: gene expression, role as neuromodulator, and functional effects. *Ann N Y Acad Sci* 519: 323–410

- Powell JFF, Zohar Y, Elizur A, Park M, Fischer WH, Craig AG, Rivier JE, Lovejoy DA, Sherwood NM (1994) Three forms of gonadotropin-releasing hormone characterized from brains of one species. *Proc Natl Acad Sci USA* 91: 12081–12085
- Schäfer H, Schulz R, Blum V (1989) Immunoreactivity to gonadotropin-releasing hormone and gonadotropic hormone in the brain and pituitary of the rainbow trout. *Cell Tissue Res* 257: 227–235
- Schreibman MP, Halpern-Sebold L, Ferin M, Margolis-Kazan H, Goos HJTh (1983) The effect of hypophysectomy and gonadotropin administration on the distribution and quantity of LHRH in the brains of platyfish: a combined immunocytochemistry and radioimmunoassay study. *Brain Res* 267: 293–300
- Schreibman MP, Margolis-Nunno H, Halpern-Sebold L, Goos HJTh, Perlman PW (1986) The influence of androgen administration on the structure and function of the brain-pituitary-gonadal axis of sexually immature platyfish, *Xiphophorus maculatus*. *Cell Tissue Res* 245: 519–524
- Schulz RW, van der Sanden MCA, Bosma PT, Goos HJTh (1994a) Effects of gonadotropin-releasing hormone during the pubertal development of the male African catfish (*Clarias gariepinus*): gonadotrophin and androgen levels in plasma. *J Endocrinol* 140: 265–273
- Schulz RW, van der Corput L, Janssen-Dommerholt J, Goos HJTh (1994b) Sexual steroids during puberty in male African catfish (*Clarias gariepinus*); serum levels and gonadotropin-stimulated testicular secretion *in vitro*. *J Comp Physiol B* 164: 195–205
- Schwanzel-Fukuda M, Pfaff DW (1989) Origin of luteinizing hormone-releasing hormone neurons. *Nature* 338: 161–164
- Seeburg PH, Adelman JP (1984) Characterization of cDNA for precursor of human luteinizing hormone releasing hormone. *Nature* 311: 666–678
- Sherwood NM, Eiden L, Brownsteine M, Soiless J, Rivier J, Vale W (1983) Characterization of teleost gonadotropin-releasing hormone. *Proc Natl Acad Sci USA* 80: 2794–2798
- Sherwood NM, Sower SA, Marshak DR, Fraser BA, Brownstein MJ (1986) Primary structure of gonadotropin-releasing hormone from lamprey brain. *J Biol Chem* 261: 4812–4819
- Sherwood NM, Lovejoy DA, Coe IR (1993) Origin of mammalian gonadotropin-releasing hormones. *Endocrine Reviews* 14: 241–254
- Sower SA, Chiang YC, Lovas S, Conlon JM (1993) Primary structure and biological activity of a third gonadotropin-releasing hormone from lamprey brain. *Endocrinology* 132: 1125–1131
- Stell WK, Walker SE, Chohan KS, Ball AK (1984) The goldfish nervus terminalis: a luteinizing hormone-releasing hormone and molluscan cardioexcitatory peptide immunoreactive olfactory pathway. *Proc Natl Acad Sci USA* 81: 940–944
- Subhedar N, Krishna NSR (1988) Immunocytochemical localization of LH-RH in the brain and pituitary of the catfish, *Clarias batrachus* (Linn.). *Gen Comp Endocrinol* 72: 431–442
- Suetake H, Kim M-H, Ashihara M, Yoshiura Y, Kikuchi K, Kobayashi M, Aida K (1995) Molecular cloning of a cDNA that encodes the precursor to a salmon-type gonadotropin-releasing hormone in the goldfish. *Proc Jpn Soc Comp Endocrinol* 10: 46
- Suzuki M, Hyodo S, Kobayashi M, Aida K, Urano A (1992) Characterization and localization of mRNA encoding the salmon-type gonadotrophin-releasing hormone precursor of the masu salmon. *J Mol Endocrinol* 9: 73–82
- Urano A, Hyodo S (1990) *In situ* hybridization techniques in the study of endocrine secretions. In “Progress in Comparative Endocrinology” Ed by A Epplé, CG Scanes, MH Stetson, Wiley-Liss, New York, pp 309–314
- White SA, Bond CT, Francis RC, Kasten TL, Fernald RD, Adelman JP (1994) A second gene for gonadotropin-releasing hormone: cDNA and expression pattern in the brain. *Proc Natl Acad Sci USA* 91: 1423–1427
- White SA, Kasten TL, Bond CT, Adelman JP, Fernald RD (1995) Three gonadotropin-releasing hormone genes in one organism suggest novel roles for an ancient peptide. *Proc Natl Acad Sci USA* 92: 8363–8367
- Wray S, Grant P, Gainer H (1989). Evidence that cells expressing luteinizing hormone-releasing hormone mRNA in the mouse are derived from progenitor cells in the olfactory placode. *Proc Natl Acad Sci USA* 86: 8132–8136
- Xiong F, Chin R, Gong Z, Suzuki K, Kiching R, Majumdar-Sonnylal S, Elsholtz HP, Hew CL (1993) Control of salmon pituitary hormone gene expression. *Fish Physiol Biochem* 11: 63–70
- Yamamoto N, Oka Y, Amano M, Aida K, Hasegawa Y, Kawashima S (1995) Multiple gonadotropin-releasing hormone (GnRH) immunoreactivity systems in the brain of the dwarf gourami, *Colisa lalia*: immunohistochemistry and radioimmunoassay. *J Comp Neurol* 355: 354–368
- Yu KL, Nahorniak CS, Peter RE, Corrigan A, Rivier JE, Vale WW (1987) Brain distribution of radioimmunoassayable gonadotropin-releasing hormone in female goldfish: seasonal variation and periovulatory changes. *Gen Comp Endocrinol* 67: 234–246
- Yu KL, Sherwood NM, Peter RE (1988) Differential distribution of two molecular forms of gonadotropin-releasing hormone in discrete brain areas of goldfish (*Carassius auratus*). *Peptides* 9: 625–630

(Received June 26, 1996 / Accepted September 9, 1996)