



A Novel G Protein α Subunit in Embryo of the Ascidian, *Halocynthia roretzi*

Authors: Iwasa, Tatsuo, Mishima, Sachiko, Watari, Ayako, Ohkuma, Mahito, Azuma, Takahiro, et al.

Source: Zoological Science, 20(2) : 141-151

Published By: Zoological Society of Japan

URL: <https://doi.org/10.2108/zsj.20.141>

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.

A Novel G Protein α Subunit in Embryo of the Ascidian, *Halocynthia roretzi*

Tatsuo Iwasa^{†*}, Sachiko Mishima, Ayako Watari, Mahito Ohkuma[‡],
Takahiro Azuma, Kazue Kanehara and Motoyuki Tsuda

Department of Life Science, Graduate School of Science, Himeji Institute of Technology,
3-2-1 Kouto, Kamigori, Akoh-gun, Hyogo 678-1297, Japan

ABSTRACT—A cDNA clone encoding a novel G protein α subunit, *HrG α_n* , was isolated from the larvae of ascidian, *Halocynthia roretzi*. In contrast with overall amino acid identity (63%) with G protein α subunit of G_i or G_o subclass, *HrG α_n* has a unique amino acid sequence, which lacks a residue for pertussis toxin substrate, but retains for cholera toxin substrate for ADP-ribosylation. The sequence characteristics and molecular phylogenetic analysis suggest that *HrG α_n* defines a novel subclass within G_i class of G protein α subunits. The zygotic expression of *HrG α_n* was first detected at the 64-cell stage and observed in all blastomeres except for B7.4, B7.5 and B7.6 cells till the 110-cell stage. As progress of the developmental stages, the expression of *HrG α_n* became restricted and was observed in the muscle, mesenchyme and a part of trunk lateral cells in tailbud embryos. With *HrG α_n* -GFP fusion-gene construct it was showed that the genomic fragment containing 2674 bp upstream of the putative translation start site of *HrG α_n* contained the regulatory sequence responsible for the expression in the muscle and mesenchyme cells, and that the regulatory sequence functioned also in *Ciona intestinalis*. Our results suggest a possible involvement of *HrG α_n* in the signaling system regulates the cell fate during the embryogenesis of the ascidian.

Key words: G protein, ascidian, *in situ* hybridization, GFP, 5'-flanking sequence

INTRODUCTION

Ascidians are lower chordates, but newly hatched tadpole larvae share a basic body plan with vertebrates. The close relationship between protochordates and the vertebrates, classically based on similarities in embryological development and the ascidian larval structural plan, has received recent support from molecular studies (Satoh and Jeffery, 1995; Corbo *et al.*, 2001; Meinertzhagen and Okamura, 2001). During embryogenesis of the ascidian the cell cleavage pattern is invariant and the cell lineage is well characterized (Nishida, 1986, 1987; Nicol and Meinertzhagen, 1988). With these advantages, the ascidian embryo is an appropriate model system for studying the molecular

mechanism of the embryonic cell specification, which includes a regulatory mechanism of a specific gene expression and a signal transduction system participating in the cell-cell interactions (Satoh, 2001; Jeffery, 2001; Nishida, 2002).

Here we focused our attention on heterotrimeric G proteins, which form a superfamily of signal transducing molecules from cell surface receptor to cytoplasmic effector (Hamm and Gilchrist, 1996; Hamm, 1998; Wilkie, 2000). The α subunits of G protein are primarily responsible for specificity to the coupling-effector molecule. They are divided into four classes (G_i, G_s, G_q and G₁₂) according to their amino acid sequence identity and the each class is composed of several subclasses; for example, G_i class is composed of G_i, G_t, G_o, and G_z subclasses. The expression pattern of G protein α subunit gene was studied in the early developmental stages in mouse (Allworth *et al.*, 1990), *Xenopus* (Otte *et al.*, 1992), and *Drosophila* (Wolfgang *et al.*, 1991), and involvement of G proteins in embryogenesis was suggested. The Wnt pathway is one of the major signaling systems, which control the development of tissues and organs (Kuehl *et al.*, 2000; Huelsken and Birchmeier, 2001). Frizzleds, cell surface Wnt-receptors, were considered as members of the G protein-coupled receptors

* Corresponding author: Tel. +81-143-46-5661;
FAX. +81-143-46-5661.

E-mail: iwasa@mmm.muroran-it.ac.jp

[†] Present address: Department of Material Science and Engineering, Muroran Institute of Technology, Mizumoto-cho, Muroran 050-8585, Japan

[‡] Present address: School of Medicine, Fujita Health University, Kutukake-cho, Toyoake, Aichi 470-1192, Japan

Note: The nucleotide sequences reported in this paper have been deposited in the DDBL/EMBL/GenBank databases under the accession numbers AB022098 and AB083069

(GPCR), because they possess seven transmembrane spanning domain. Recently it was established that Frizzleds are really members of GPCR and couple with G protein (Wu *et al.*, 2000; Liu *et al.*, 2001). In embryos of *Ciona savignyi* nuclear accumulation of β -catenin, an essential component of the Wnt signaling pathway, was reported as a most probable first step of endodermal cell specification and one of the genes downstream of β -catenin was found to be responsible for the endoderm differentiation (Imai *et al.*, 2000; Satou *et al.*, 2001).

In this paper, we describe the isolation of *HrG α_n* , a cDNA encoding a novel G protein α subunit, from cDNA library of tadpole larvae of a solitary ascidian, *Halocynthia roretzi*. Based on the comparison of the deduced amino acid sequence and molecular phylogenetic analysis, we concluded that *HrG α_n* defines a novel subclass within G protein α subunits of G_i class. The spatio-temporal expression pattern was studied by northern blot analysis and whole-mount *in situ* hybridization. The genomic fragment containing the regulatory sequence responsible for the site-specific expression in tailbud embryos was obtained from *H. roretzi*, and was shown to function also in *Ciona intestinalis*. Based on these findings, a possible involvement of *HrG α_n* -signaling in embryogenesis of the ascidian was discussed.

MATERIALS AND METHODS

Animals, Eggs and Embryos

Halocynthia roretzi were purchased from fishermen at Wakkanai, Hokkaido, Japan, and transported to the Cell Biology Center of Himeji Institute of Technology, where animals were kept at 5°C under the constant illumination until use. Naturally spawned eggs were collected with a mesh of an appropriate pore size (200 μ m), were fertilized with a suspension of non-self sperm and were incubated in artificial seawater (Aquamarine, Senju, Osaka, Japan) at 13°C. At this temperature, embryos developed into 64-cells, gastrulae, and early tailbud stages about 6, 10, and 20 hr after fertilization, respectively. At 35 hr after fertilization tadpole larvae hatched. Removal of the chorion was done mechanically with sharpened tungsten needles.

Ciona intestinalis were collected from several locations of Aioi-bay, Hyogo, Japan. Handling of eggs and embryos were according to Nakagawa *et al.* (1999).

Polymerase Chain Reaction (PCR)

Degenerated PCR primers were designed according to the conserved amino acid motifs of G protein α subunits. A forward primer was directed against the C-domain corresponding to amino acid sequence KKWI(H/Q)CF and a reverse primer, G-domain corresponding to amino acid sequence LFLNKKD (GF22 and GR22, respectively) (Iwasa *et al.*, 2000, 2001). Polymerase chain reactions were performed with 1 μ l aliquots of cDNA library of tadpole larvae of *H. roretzi* (λ ZAPII, Stratagene, La Jolla, USA; kind gift from Dr. N. Satoh, Kyoto University) in 15 μ l reactions. PCR products of the expected size (ca. 200 bp) were subcloned in pT7blue vector (Stratagene, La Jolla, USA). Nucleotide sequences were determined for both strands with the primer-labeled cycle sequencing kits (Amersham Pharmacia Biotech, Uppsala, Sweden) and an automatic DNA sequencer (Shimadzu DSQ 1000L, Shimadzu, Kyoto, Japan).

Isolation of cDNA clones

A cDNA library of tadpole larvae of *H. roretzi* was screened

with random primed 32 P-labeled PCR-*HrG α* (Fig. 1A) probe (Megaprime DNA labeling system, Amersham Pharmacia Biotech, Uppsala, Sweden) by hybridization in 45% formamide, 6 \times SSC, 1% SDS, 5 \times Denhardt's solution, 20 μ g/ml denatured salmon sperm DNA at 42°C overnight. Afterwards, the filters were washed twice in 2 \times SSPE, 0.1% SDS for 10 min at RT, and twice in 1 \times SSPE, 0.1% SDS for 15 min at 65°C. Among 1.0 \times 10⁵ plaques we obtained only one positive plaque containing *HrG α -1* (Fig. 1A), which lacks C-terminal sequence. We further screened the cDNA library (1.2 \times 10⁵ plaques) with *HrG α -1* as a probe, and obtained a new positive plaque containing *HrG α -2* (Fig. 1A).

Northern blot analysis

Total RNA was prepared with standard CsCl-ultracentrifugation methods (Ausubel *et al.*, 1987) from eggs or embryos of the desired stage. The total RNA (10 μ g) was separated on 0.8% agarose-formamide gel and transferred to nylon membrane (Hybond N⁺, Amersham Pharmacia Biotech, Uppsala, Sweden). The membrane was cross-linked by UV cross-linker (CL-1000 Ultra Violet Cross Linker, UVP, San Gabriel, USA). Hybridization was carried out by the same procedure as described under "Isolation of cDNA clones", with 32 P-labeled *HrG α -3'* probe, *Hinc* II - *Pst* I fragment of *HrG α -2* (Fig. 1A). The washed membranes were analyzed with an imaging plate (BAS 2000, Fuji Film, Tokyo, Japan).

Southern blot analysis

Chromosomal DNA from sperm of *H. roretzi* was prepared according to a standard procedure (Davis *et al.*, 1986). Ten μ g of the genomic DNA was digested with *Eco* RI, *Bam* HI, *Hind* III or *Pst* I, electrophoresed on 0.7% agarose gel, and then transferred to nylon membranes. The membranes were hybridized, washed as described under "Isolation of cDNA clones", and then analyzed with an imaging plate (BAS 2000, Fuji Film, Tokyo, Japan).

In situ hybridization

Whole-mount specimens at various developmental stages of *H. roretzi* were hybridized *in situ* using Digoxigenin (DIG)-labeled anti-sense and sense RNA probes (DIG RNA labeling Kit, Roche, Japan). The procedures were mainly according to Yasuo and Satoh (1994).

Cloning of 5'-flanking sequence of *HrG α_n*

The genomic library of *H. roretzi* (kind gift from Dr. N. Satoh, Kyoto University) was screened with 32 P-labeled *HrG α -1* probe using standard procedures (Davis *et al.*, 1986). The phage DNA was prepared from the cloned phage and used as a template for the following PCR amplification. The 5'-flanking sequence of *HrG α_n* was obtained with PCR using a combination of a gene-specific (CTTCATAGTCGATTCCGAGC; nt 354-373 for *HrG α_n*) and a vector-specific primer (T3 or T7 primer, Toyobo, Osaka, Japan). PCR was performed for 30 cycles of 1 min template denaturation at 95°C, 1 min primer annealing at 50°C, 5 min primer extension at 72°C with Expand High Fidelity PCR system (Roche, Tokyo, Japan). The longest PCR fragment (ca. 6.0 kb) was cloned into pT7blue vector (Stratagene, La Jolla, USA) (Gn6.0-pT7b) and the nucleotide sequence was determined in both strands with a series of deletion products (Deletion Kit for Kilo-Sequence, Takara, Kusatsu, Japan). A 3.5 kb fragment was also cloned into pT7blue vector (Gn3.5-pT7b) and was used for preparation of GFP-fusion construct.

Fusion gene construct and microinjection

Fusion construct was prepared using Gn3.5-pT7b plasmid, which contains 2674 bp upstream and 244 bp downstream sequence from the putative translation start-site of *HrG α_n* . Gn3.5-pT7b was double-digested with *Sac* I and *Bam* HI, and then fused with a DNA fragment encoding GFP (a *Sac* I-*Bam* HI fragment of

pAcPr-GFP, kind gift from Dr. Y. Okamura, NIPS). The resulted fusion construct was pGn3.5-GFP. The *Sac* I-*Bam* HI fragment of the pAcPr-GFP was cloned into pT7blue vector and the construct, (-)-GFP, was used as the reference. Microinjection of the fusion construct into fertilized eggs of *H. roretzi* was performed according to Takahashi *et al.* (1999). In the case of *C. intestinalis*, the fusion construct was electroporated into fertilized eggs according to Corbo *et al.* (1997). The expression of GFP was observed by fluorescent-stereomicroscopy (SZX-12, Olympus, Tokyo, Japan).

RESULTS

Isolation of cDNA clones encoding HrGα_n

We obtained a cDNA fragment PCR-HrGα showing high similarity (76%) in the deduced amino acid sequence to that of rat G protein α subunit of G_i class (Fig. 1A). Two

cDNA inserts, HrGα-1 and HrGα-2 were obtained by screening of a cDNA library of tadpole larvae of *H. roretzi* as described in Materials and Methods. HrGα-1 (927 bp) lacked C-terminal sequence. HrGα-2 (2397 bp) contained C-terminal and 3'-noncoding sequence with poly(A) tract, which overlapped 612 bp with HrGα-1. An open reading frame encoding 357 amino acids (calculated molecular mass: 40532 Da.) was deduced from the nucleotide sequences of HrGα-1 and -2. Three possible polyadenylation signals (AATAAA) are found at 1626-1631, 2043-2048 and 2629-2634. The nucleotides at 1895-1992 (TTTTTAT) are the sequence that activates polyadenylation of messages during maturation in *Xenopus* oocyte (Fox *et al.*, 1989).

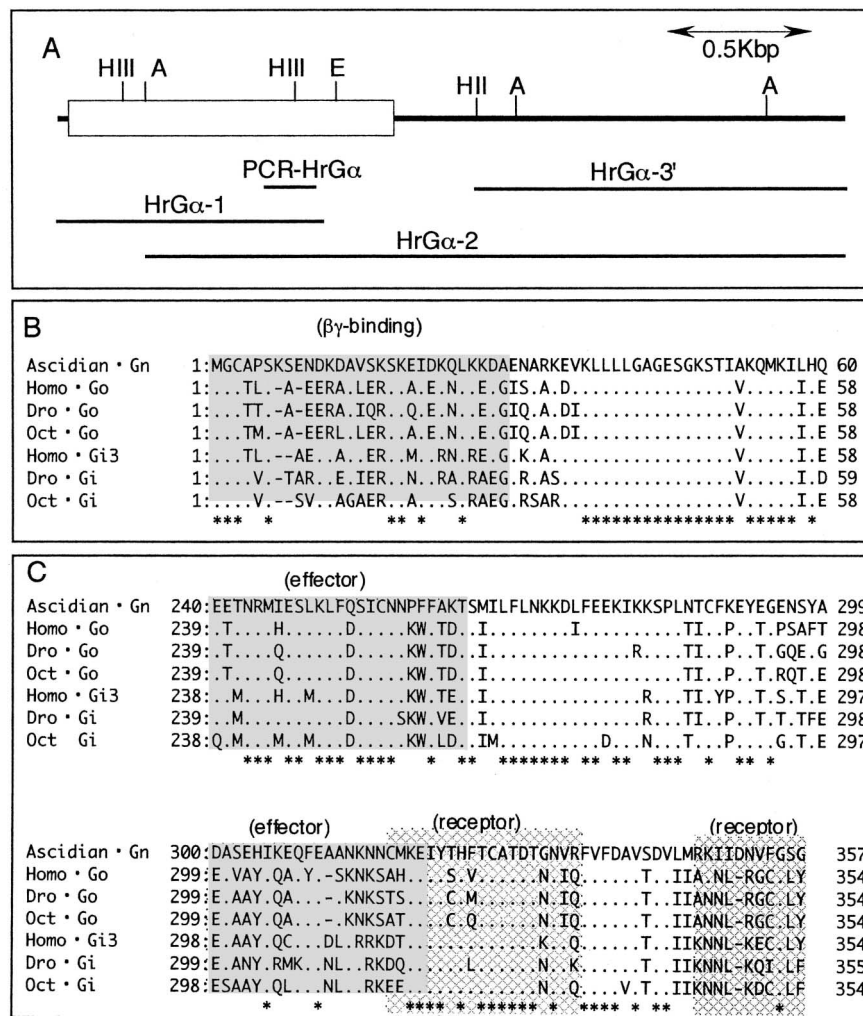
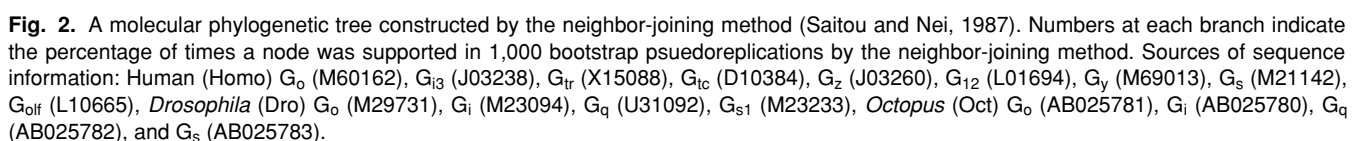


Fig. 1. Molecular characterization of HrGα_n. (A): Schematic representation and restriction map of HrGα_n. Open box represents protein-encoding region. Straight line represents 5' and 3'-untranslated sequence. The PCR clone, PCR-HrGα, and two cDNA clones, HrGα-1 and HrGα-2, are shown underneath. HrGα-3' is the *Hinc* II - *Pst* I fragment of the 3'-noncoding region of HrGα_n and was used as a probe for the northern blot analysis. A; *Acc* I, E; *Eco* RI, HII; *Hinc* II, HIII; *Hind* III. (B) and (C): Comparison of the amino acid sequence of N-terminal region (B) and that of C-terminal region (C) of HrGα_n with that of G protein α subunits of G_o and G_i subclass of human (Homo), *Drosophila* (Dro) and *Octopus* (Oct). Dots represent identical amino acids, and dashes, introduced gaps. The asterisks indicate the conserved amino acids among all sequences. The location of interaction sites with Gβγ subunit or effector, or receptor are indicated above the sequences. Sources of sequence information: Human G_o (M60162), G_{i3} (J03238), *Drosophila* G_o (M29731), G_i (M23094), *Octopus* G_o (AB025781) and G_i (AB025780). The nucleotide sequence of HrGα_n is available at DDBJ/EMBL/GenBank with an accession number AB022098.

Although the amino acid sequence of the guanine nucleotide pocket of HrG α_n was highly conserved, overall amino acid sequence exhibited a rather low degree of iden-

To investigate evolutionary relationships between HrGα_n and known metazoan Gα isoforms, phylogenetic tree was constructed with the neighbor-joining method (Saitou and Nei, 1987)(Fig. 2). The phylogenetic tree reveals that



HrG α_n is most closely related to G α_i and that it should be a member of G α_i class. Within the G α_i class, however, HrG α_n was fairly diverged from any subclasses, G α_i , G α_o , G α_t , and G α_z .

Southern blot analysis of the ascidian genomic DNA

Southern blot analysis of ascidian genomic DNA was performed with HrG α -1 as a probe. As shown in Fig. 3A, the HrG α -1 probe detected a single band in the genomic DNA digested with *Bam* HI, *Eco* RI, or *Hind* III. In the digests with *Pst* I the main band was observed at about 15 kb and an additional weak band was observed at about 1.9 kb. Judging from these results, it is very likely that HrG α_n is a single copy gene.

Spatio-temporal expression pattern of the HrG α_n transcripts

To examine the temporal expression of HrG α_n during ascidian embryogenesis, northern blot analysis was performed with eight different developmental stages from the unfertilized egg up to the tadpole larva with 32 P-labeled HrG α -3' as a probe. The signal of HrG α_n was observed at about 3.2 kb in the unfertilized egg indicating presence of maternal mRNAs of HrG α_n (lane 1 in Fig. 3B). The signal became slightly weaker as the progress of development

until the 64-cell stage. At the 64-cell stage, the transcripts gave more clear signal (lane 5 in Fig. 3B) and intensity of the signal increased in the later stages, indicating the zygotic expression starts from the 64-cell stage up to tadpole larvae (lanes 5 - 8 in Fig. 3B). After an overnight exposure of the hybridized membrane to the BAS analyzer, two additional bands of 2.5 and 1.8 kb were detected after gastrula stage (data not shown). These three types of mRNAs different in size probably correspond to three possible polyadenylation sites found in HrG α -2. The expression of HrG α_n in the adult tissues was also investigated (Fig. 3C). The clear signal of HrG α_n was detected at about 3.2 kb in all tissues examined. The expression in the branchial sac, ganglion and intestine were rather higher than in stomach and ovary. Thus, HrG α_n is expressed in both larvae and adult tissues.

The spatial distribution of expression of HrG α_n was investigated in developing embryos with whole-mount *in situ* hybridization. The maternal mRNAs of HrG α_n were detected evenly in the entire region of the cytoplasm of the unfertilized egg (data not shown). As shown in Fig. 4A - D, no obvious difference in the signal was observed in each blastomere in the 16-cell and 32-cell stage, indicating that the maternal mRNAs were divided evenly to each blastomere.

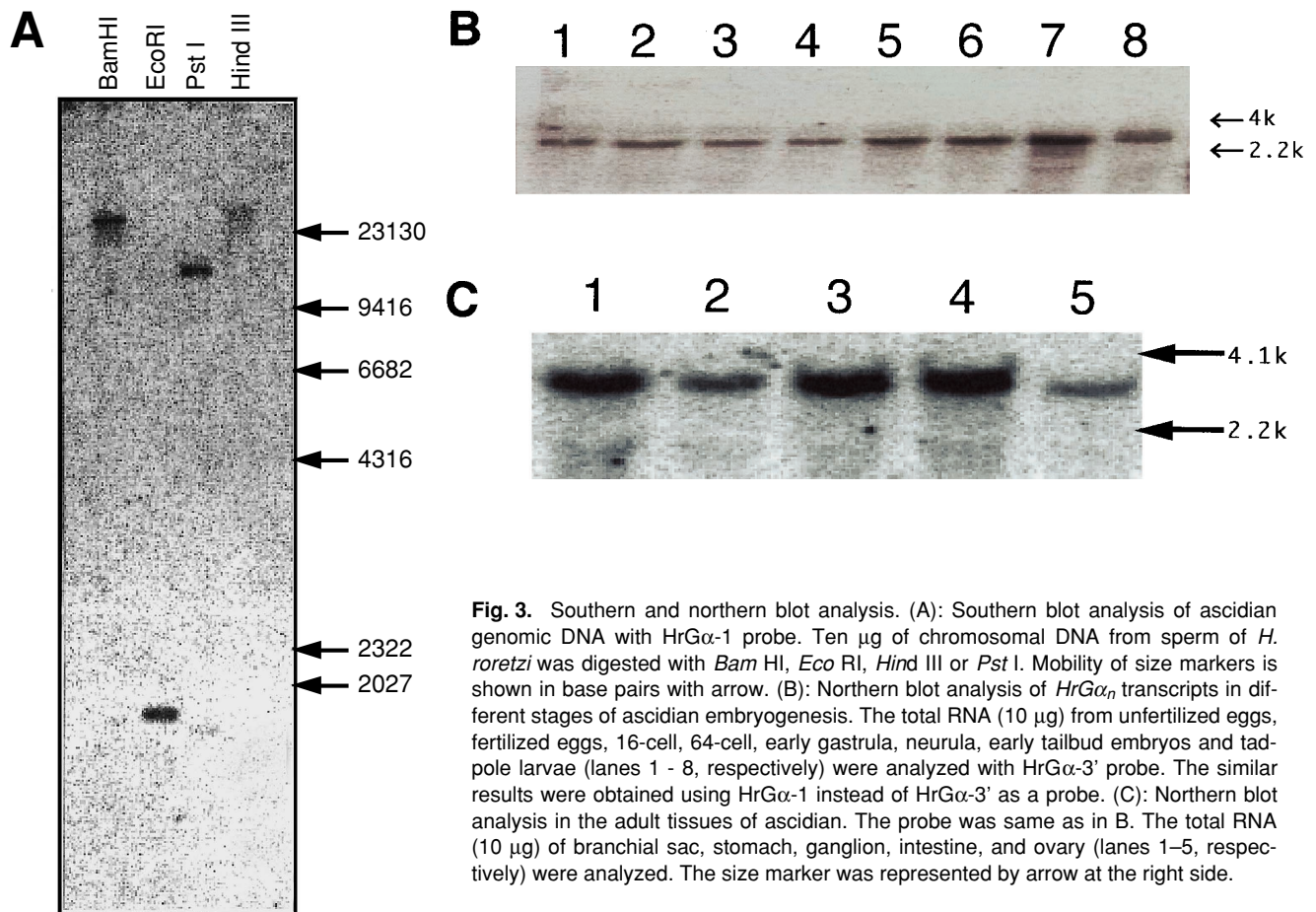


Fig. 3. Southern and northern blot analysis. (A): Southern blot analysis of ascidian genomic DNA with HrG α -1 probe. Ten μ g of chromosomal DNA from sperm of *H. roretzi* was digested with *Bam* HI, *Eco* RI, *Hind* III or *Pst* I. Mobility of size markers is shown in base pairs with arrow. (B): Northern blot analysis of HrG α_n transcripts in different stages of ascidian embryogenesis. The total RNA (10 μ g) from unfertilized eggs, fertilized eggs, 16-cell, 64-cell, early gastrula, neurula, early tailbud embryos and tadpole larvae (lanes 1 - 8, respectively) were analyzed with HrG α -3' probe. The similar results were obtained using HrG α -1 instead of HrG α -3' as a probe. (C): Northern blot analysis in the adult tissues of ascidian. The probe was same as in B. The total RNA (10 μ g) of branchial sac, stomach, ganglion, intestine, and ovary (lanes 1-5, respectively) were analyzed. The size marker was represented by arrow at the right side.

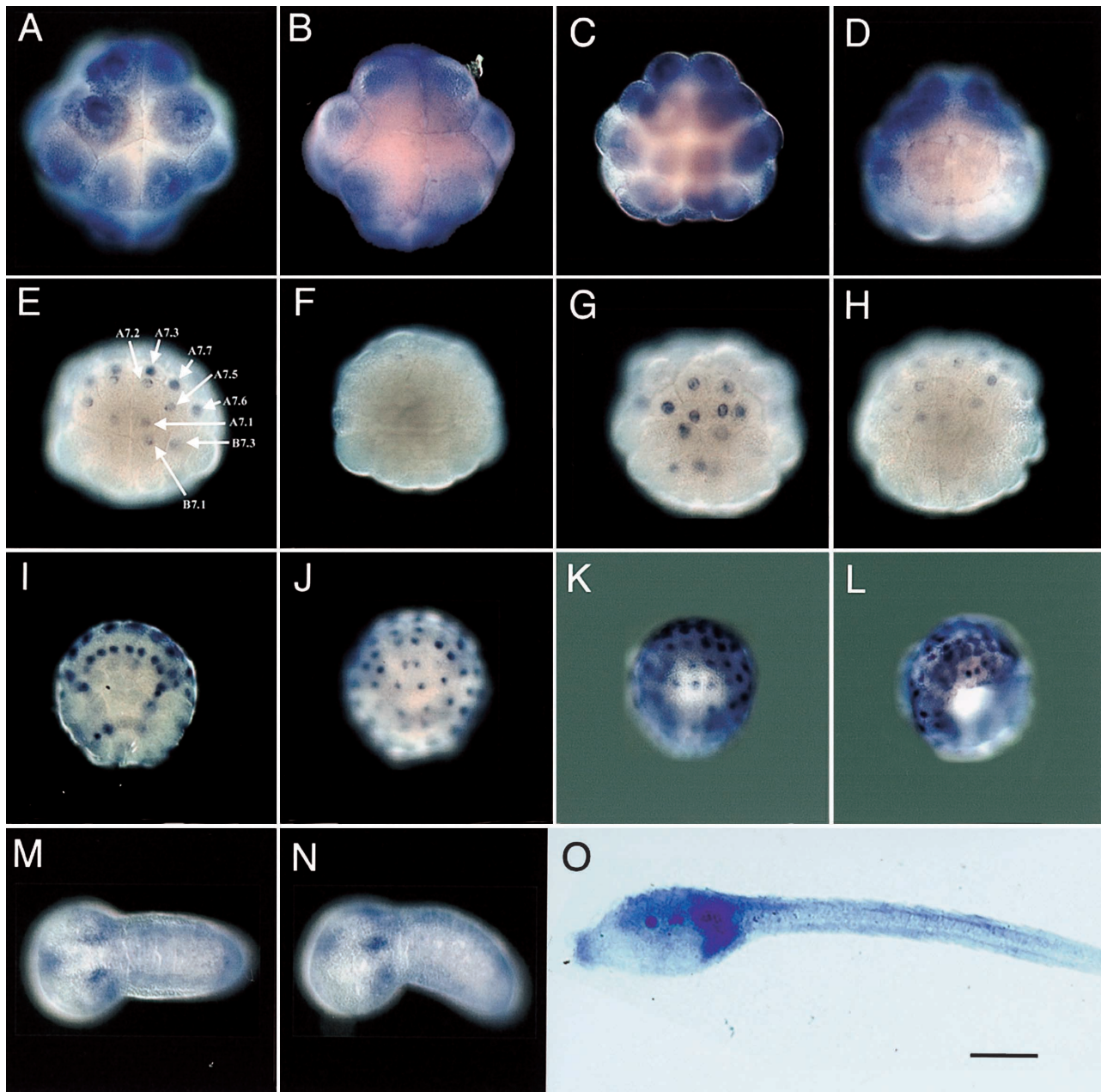


Fig. 4. Whole-mount *in situ* hybridization of developing embryos with a Digoxigenin-labeled antisense probe for *HrGα_n* message. (A) and (B): A 16-cell embryo (animal view and vegetal view, respectively). (C) and (D): A 32-cell embryo (animal view and vegetal view, respectively). (E) and (F): A 64-cell embryo (animal view and vegetal view, respectively). (G) and (H): A 76-cell embryo (animal view and vegetal view, respectively). (I) and (J): A 110-cell embryo (animal view and vegetal view, respectively). (K) and (L): Gastrula (animal view and vegetal view, respectively). (M) and (N): Early tailbud embryo, dorsal and lateral view, respectively. (O): A tadpole larva. Scale bar=100 μm.

The observed temporal expression patterns of *HrGα_n* from the 64-cell to 110-cell stage were summarized in Fig. 5. At the 64-cell stage embryo, zygotic expression of *HrGα_n* was first detected in the nuclei of all A-line cells and two B-line cells (B7.1 and B7.3) (Fig. 4E and F). No signal was observed in a- and b-line cells at this stage. In the later developmental stages (the 76-cell and 110-cell stage), the expression was observed in all A- and a-line cells except for A7.1 and A7.2 cells, which showed the signal at the 64-cell and 76-cell stage and did not at the 110-cell stage. The

daughter cells of A7.3, A7.4, A7.7 and A7.8 cells did not showed the expression signal at the 76-cell stage, but showed at the 110-cell stage. In the B-line cells, only four pairs of blastomeres showed the signal during the stages. The B7.1 and B7.2 cells showed the expression signal at the 64-cell and/or 76-cell stage, but not at the 110-cell stage. They develop into endoderm or endodermal strand. The B7.3 cell showed the expression at the 64-cell stage, but two daughter cells did not at the 76-cell stage. At the 110-cell stage, one of the daughter cell, the B8.5 cell, showed

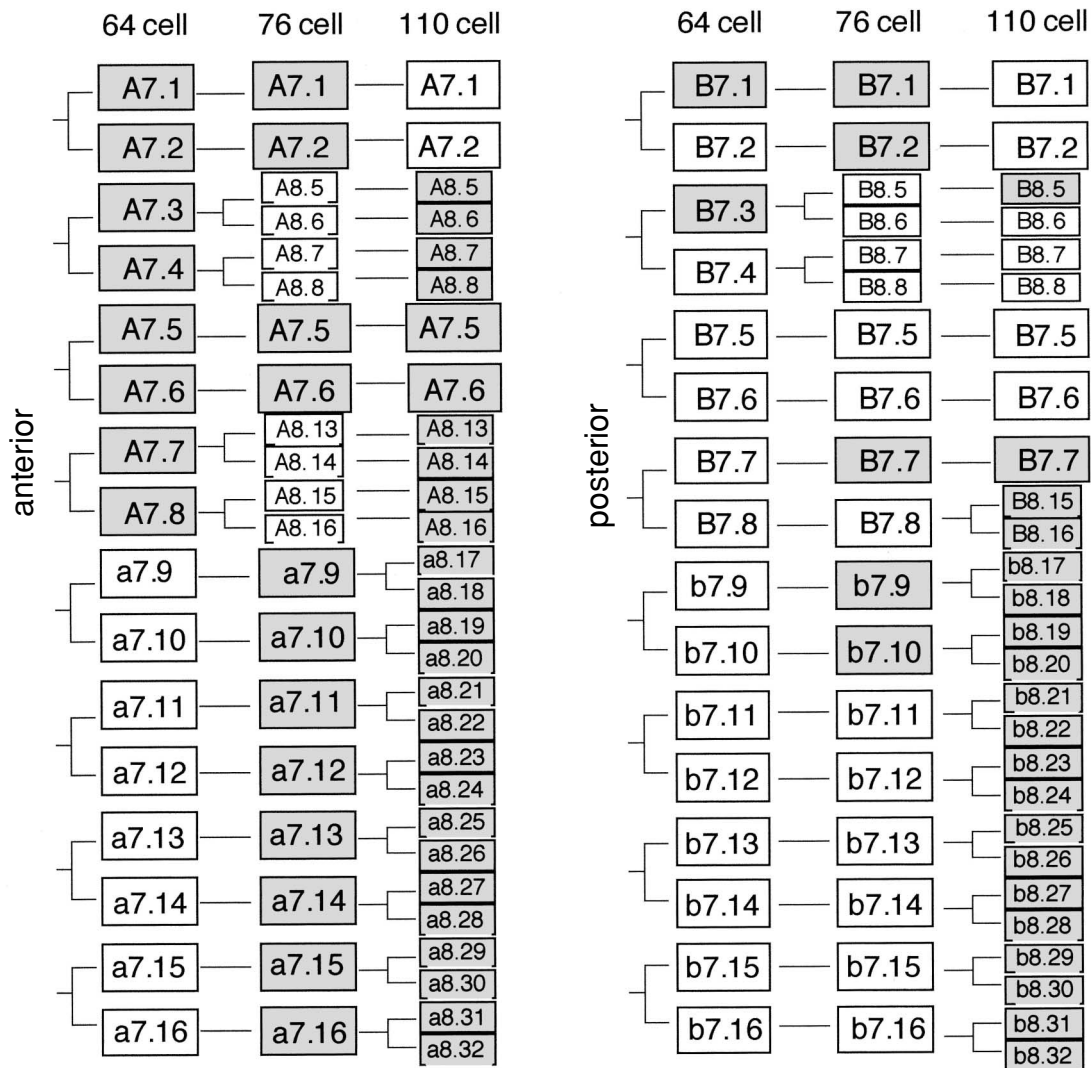


Fig. 5. Zygotic expression of HrGα_n at the 64-cell, 76-cell and 110-cell stage as summarized referring to the cell lineage. The names of blastomeres where the expression of HrGα_n was detected are presented in shaded boxes. The cell lineage is according to Nishida (1987).

the expression, but another daughter cell, the B8.6 cell, did not. Their cell fate was determined at this stage. The B8.5 cell develops into the mesenchyme and the B8.6 cell develops into the notochord. The B7.7 cell showed the expression at the 76-cell and 110-cell stage. The B7.7 cell develops into mesenchyme. The other cells (B7.4, B7.5, B7.6 and B7.8 cells) and their descendants did not show the expression at these stages. They give rise to muscle, endoderm or endodermal strand. The expression in the b-line cells was observed at the 110-cell stage. Exceptions were the case in b7.9 and b7.10 cells (containing the muscle, spinal cord, endodermal strand, epidermis and brain stem lineage cells), which showed expression in both the 76-cell and 110-cell stage.

In the early tailbud stage, the expression was detected in the muscle cells of the tail and the ventral portion of the mesenchyme. A weak expression was observed in a dorsal region of the trunk, some of trunk lateral cells and also several cells of the brain stem (Fig. 4M and N). In a tadpole

larva, a strong expression of HrGα_n was observed in mesenchyme cells of the posterior trunk region and a weak expression was observed in a dorsal region of the trunk (Fig. 4O).

The 5'-flanking sequence of HrGα_n

In order to analyze the regulatory sequence responsible for observed spatio-temporal expression of HrGα_n, we isolated the 5'-flanking sequence of HrGα_n from a genomic library of *H. roretzi*. The longest PCR fragment (Gn6.0-pT7b) contains 5478 bp upstream of the putative translation start site and 244bp downstream (Fig. 6A). The possible ORFs longer than 200 bp were searched in the upstream sequence. Seven ORFs (201–339 bp) were found in *cis*-direction to HrGα_n and four (201–339 bp) in *trans*-direction. The amino acid sequences similar to those deduced from the putative ORFs were searched against GenBank database and we did not find out any sequence with high similarity. The results suggest that there is no gene in the

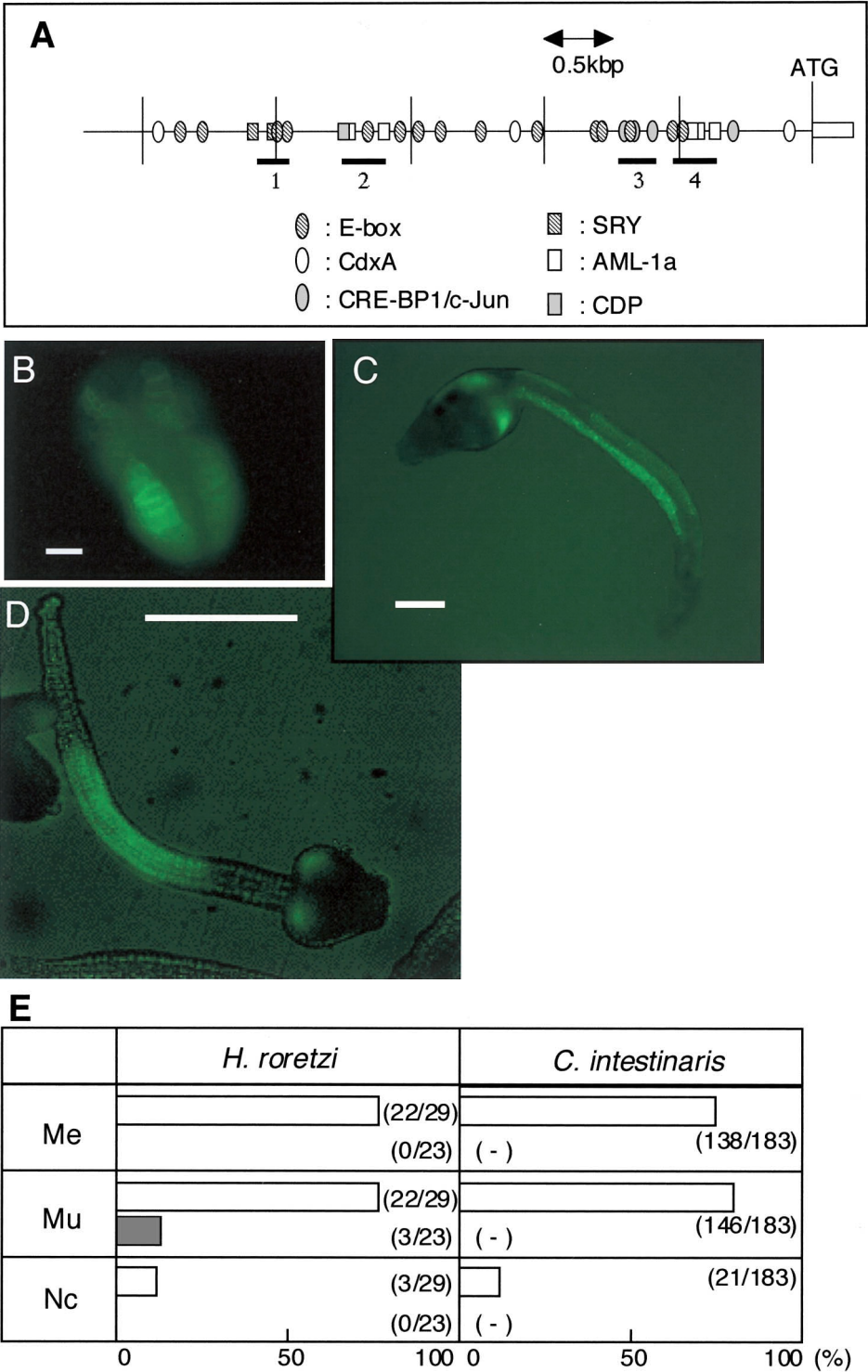


Fig. 6. (A): Schematic representation of sequence motifs in the 5'-flanking sequence of *HrGα_n* gene. Putative binding sites for transcription factors were searched against the TRANSFAC database using TRANSFAC Find (Heinemeyer *et al.*, 1999) and also with Genetyx Mac (Genetyx, Tokyo, Japan). The thick lines under the sequence indicate the clusters of the potential binding motif(s) and E-box motif. (B) and (C): Expression of *HrGα_n*-GFP fusion genes. pGn3.5-GFP was injected in fertilized egg of *H. roretzi*. The expression of GFP in the early tailbud embryo (B) and the hatched larva (C). (D): 3.5Gn-GFP was introduced via electroporation into fertilized eggs of *Ciona intestinalis*. GFP expression was observed in muscle and mesenchyme cells of hatched larva. Scale bar; 100 μm. (E): Frequency of embryos with GFP expression, which developed from eggs carrying *HrGα_n*-GFP fusion constructs. The sites of the expression were shown on the left (Me; mesenchyme, Mu; muscle, Nc; notochord). Open boxes represent the results of 3.5Gn-GFP. The shaded box represents the result of injection of (-)-GFP. Numerals in parentheses indicate number of positive embryos relative to total embryos examined. (-); Not tested. The nucleotide sequence of the 5'-flanking sequence of *HrGα_n* gene is available at DDBJ/EMBL/ GenBank with an accession number AB083069.

upstream sequence of 5478 bp.

The sequence motifs of the potential binding site for transcription factors in the 5'-flanking sequence were searched against the TRANSFAC database (Heinemeyer *et al.*, 1999). The results were summarized in Fig. 6A. We found 15 E-box motifs (CANNTG) at -4713, -4529, -4022, -3909, -3359, -3094, -2944, -2795, -2444, -2072, -1792, -1609, -1404, -1013, and -990 bp from the putative translation start site of HrG α_n . There were four clusters of the potential binding motif(s) and E-box motif. We tentatively designated them as Cluster 1–4 (thick lines in Fig. 6A). Cluster 1 (-4106 to -3909) consisted of two SRY motifs (-4160 and -4004) and two E-box motifs (-4022 and -3909). Cluster 2 (-3482 to -3203) consisted of one CDP motif (-3482), two AML-1a motifs (-3445 and -3203) and an E-box motif (-3359). AML-1a motif is a potential binding site of AML-1a protein, a central 118 amino acid domain of which shows 69% homology to the *Drosophila* pair-rule gene, *runt* (Meyers *et al.*, 1993). CDP motif is a potential binding site of Cut-like homeodomain protein (Harada *et al.*, 1995). Thus, Cluster 2 consisted of potential binding sites for proteins known to regulate cellular development. Cluster 3 (-1404 to -1180) consisted of two CREB motifs (-1310 and -1180), a CRE-BP1/c-Jun motif (-1403) and an E-box motif (-1404). Cluster 4 (-1013 to -729) consisted of two E-box motifs (-1013 and -990) and three AML-1a motifs (-883, -863 and -729). There were three CdxA motifs at -4880, -2235 and -148bp, but they do not form a cluster with the other motifs.

Expression of the fusion construct in embryos of *H. roretzi* and *C. intestinalis*

To analyze the regulatory activity of the 5'-flanking region of HrG α_n , we constructed a fusion gene of the 5'-flanking sequence of HrG α_n and the DNA fragment encoding GFP, and injected them into fertilized eggs of *H. roretzi*. The construct, pGn3.5-GFP, contains 2674 bp upstream of the putative translation start site and 244bp downstream of HrG α_n . The upstream-sequence of 2674 bp directs expression of GFP gene in a pattern that is virtually identical to the endogenous gene. The fluorescence from the GFP was first observed in the initial tailbud stage (Fig 6B), suggesting the expression in the earlier stages was too weak to detect the fluorescence. The fluorescence from GFP was observed primarily in the muscle and mesenchyme cells (Fig. 6B and C). In a few embryos, the expression of GFP was observed in the notochord or posterior sensory vesicles (Fig. 6C). The injection of the fusion construct without the 5'-flanking sequence of HrG α_n ((-)-GFP) resulted in few expression of GFP with three exceptions observed in the muscle cells (Fig. 6E, left).

The electroporation of the pGn3.5-GFP into the fertilized eggs of *C. intestinalis* resulted in the expression of GFP in the muscle and mesenchyme cells (Fig. 6D). The expression pattern was same as in *H. roretzi*. Small numbers of the embryos showed an ectopic expression of GFP in the notochord or brain stem (Fig. 6E, right).

DISCUSSION

In this study, we described a novel G protein α subunit, HrG α_n , of ascidian tadpole larvae. The deduced amino acid sequence of HrG α_n (357 amino acids) showed higher similarity to human G α_i and G α_o . There was a candidate sequence for palmitoylation in the N-terminal region of HrG α_n , which is conserved in G α_i (Chen and Manning, 2001). The phylogenetic tree constructed based on the deduced amino acid sequence clearly showed that HrG α_n is a member of G α_i . However, HrG α_n was unique among those belong to G α_i in the following criteria. First of all, the deduced amino acid sequence of HrG α_n lacked the cysteine residue in its C-terminal region. The cysteine residue is a substrate of ADP-ribosylation by pertussis toxin, which is conserved in almost all G α_i . HrG α_n , however, possessed an arginine residue positioned at 180 (R180), which is a possible substrate of cholera toxin, and ADP-ribosylated in G α_t and G α_s . Second, the amino acid sequence of C-terminal region was extensively different from that of the other G α_i (Fig. 1C). Third, HrG α_n was fairly diverged from any other members of G α_i in the phylogenetic tree (Fig. 2). Based on these results we concluded that HrG α_n defines a novel subclass in G protein α subunits of G α_i class.

The zygotic expression of HrG α_n was first observed at the 64-cell stage. From the 64-cell to 110-cell stage, a transient expression of HrG α_n was observed in all cells except B7.4, B7.5 and B7.6 cells. An interesting expression pattern of HrG α_n was observed in the case of the B7.3 cell. The B7.3 cell showed expression of HrG α_n in the 64-cell stage, but two daughter cells did not in the 76-cell stage. At the 110-cell stage, one of the daughter cell, the B8.5 cell, showed the expression, but another daughter cell, the B8.6 cell, did not. Their cell fate was determined at this stage. The B8.5 cell develops into the mesenchyme and the B8.6 cell develops into the notochord. The results suggest a possibility that expression of HrG α_n is related to determination of their cell fate. Kim and Nishida found that formation of mesenchyme cells requires cellular interaction that suppresses muscle fate in the mesenchyme precursor blastomeres (Kim and Nishida, 1999). They further mentioned about two possibilities about the formation of mesenchyme cells. One is that suppression of muscle fate is enough to allow cells to choose a mesenchyme pathway and another is that suppression of the muscle fate and promotion of mesenchyme formation are distinct processes. If the latter is the case, it seems likely that HrG α_n is involved in promotion of mesenchyme formation. Concerning about this issue the expression pattern of HrG α_n in daughter cells of the B6.4 cell should be noted. The B7.8 cell, a daughter cell of the B6.4 cell, gives rise to muscle cells and another daughter cell (B7.7), to mesenchyme cells. The expression of HrG α_n was not observed in the B7.8 cell, but observed in the B7.7 cell in the 76-cell and 110-cell stage.

The expression of HrG α_n in the mesenchyme cells con-

tinued and became stronger in the tadpole larva (Fig. 4M–O). In tadpole larvae the strong expression was also observed in trunk lateral cells (TLC). The TLC is one of the mesodermal tissues of a larva and categorize as a kind of embryonic mesenchyme cell (Satoh, 1994). The A7.6 cell, only one TLC precursor cell, showed expression of *HrGα_n* from the 64-cell to 110-cell stage. These results showed that expression of *HrGα_n* was observed in mesenchyme and their precursor cells, suggesting another possible role of *HrGα_n*, maintenance of mesenchyme cells. The physiological meaning of the transient expression in the other cells from the 64-cell to 110-cell stage is remained to be elucidated.

The expression of pGn3.5-GFP in embryos of *H. roretzi* was observed in a pattern that is virtually identical to the endogenous gene, in the muscle and mesenchyme cells in the early tailbud stage. The results indicate that the upstream-sequence of 2674 bp contains a regulatory sequence responsible for expression of *HrGα_n* in the muscle and mesenchyme cells. Araki and Satoh investigated the regulatory sequence for muscle specific expression of *HrMHC1* (*H. roretzi* muscle myosin heavy-chain) gene, compared it with that of *HrMA4* (*H. roretzi* muscle actin) gene and found several common motifs between them (Araki and Satoh, 1996). They were Box A (TACGAAT), E-box/Box B (CAGTTGCGC), GATA binding site (TGATAG), and Box T1/T2 (Box T; TTTTCTTTCA) and their results suggest that the BoxT1/T2 is critical for the promoter activity of the *HrMHC1* gene. Because the expression of pGn3.5-GFP was observed in the muscle cells, we searched in the 5'-flanking sequence contained in pGn3.5-GFP for these motifs and found one GATA binding site (TGATAA) at -721 and one Box T1 (TTTTTTC) at -2347 in *HrGα_n*. The box T1 found in the upstream region of *HrGα_n* was not so proximal as the Box T1/T2 found in the upstream region of *HrMHC1* gene. In more upstream region than that contained in pGn3.5-GFP two potential GATA binding site (WGATAR) existed in Cluster 2 (-3482 to -3203). They were overlapped in the sequence, AGATAGATAG, between -3260 and -3251. Thus, the regulatory mechanism for expression in the muscle cells of the *HrGα_n* gene would be rather different from that of the *HrMHC1* gene. The muscle-expression of pGn3.5-GFP was also observed in electroporated embryos of *C. intestinalis*, suggesting that the regulatory mechanism seems common in *H. roretzi* and *C. intestinalis*. In the case of notochord specific expression, p(-289)As-T/lacZ, a construct of the 5'-flanking region of *As-T* gene of *H. roretzi* and the reporter gene (*lacZ*), showed notochord specific expression in *Ciona* embryos (Takahashi *et al.*, 1999). However, the minimal promoter system for the notochord-specific expression seems different between *As-T* and *Ci-Bra*. The present results suggest that the upstream-sequence of 2674 bp of *HrGα_n* contains a regulatory sequence responsible for expression of *GFP* gene in the muscle and mesenchyme cells in *H. roretzi* and also in *C. intestinalis*. The minimal promoter system for *HrGα_n* expression should be elucidated for

more detailed consideration.

Four clusters of the sequence motifs of the potential binding site for transcription factors were found in the 5'-flanking sequence of *HrGα_n* (Fig. 6A). Two of them, Clusters 2 and 4 consisted of sequence motifs for AML-1a, CDP, E-box and/or GATA. Cluster 3 consisted of sequence motifs for CREB and E-box. Cluster 1 consisted of sequence motifs for CDP and E-box. The homologues of the transcription factors possibly bind to these sequence motifs are found in the EST library of *C. intestinalis* (Satou *et al.*, 2002), suggesting that these transcriptional factors are involved in regulation of gene expression in *C. intestinalis*. Whether or not these transcriptional factors function in *H. roretzi* and regulate the expression of *HrGα_n* gene is remained to be elucidated.

The clarification of the physiological function of *HrGα_n*, its effector(s) and receptor(s) is also remained to be elucidated. An *HrGα_n*-homologue was recently found from planarian central nervous system, which is specifically expressed in the distal part of brain lateral branches (Cebria *et al.*, 2002). Unfortunately the physiological role of the gene product was not reported and the homologue belongs to the same subclass is not found yet from the other animals. Thus, we cannot expect physiological function of *HrGα_n* by analogy. On this issue it should be noted that the amino acid sequence of *HrGα_n* was quite unique in its C-terminal region, which is a possible interaction site of G protein α subunit with its receptor molecule (Hamm *et al.*, 1988; Nishimura *et al.*, 1998; Gilchrist *et al.*, 2002). It can be expected that *HrGα_n* couple with a novel receptor.

ACKNOWLEDGEMENTS

We thank Drs. N. Satoh and Y. Okamura for providing the cDNA library of larvae of *H. roretzi* and kind technical advises. Thanks are also due to the members of Asamushi Marine Biological Laboratory of Tohoku University, and the Ushimado Marine Biological Laboratory of Okayama University for facilitating the collection of animals. This work was supported in part by Grant-in-Aid from the Ministry of Education, Science, Culture and Sports, Japan to M. T. and, to T. I.

REFERENCES

- Allworth AE, Hildebrandt JD, Ziomek CA (1990) Differential regulation of G protein subunit expression in mouse oocytes, eggs, and early embryos. *Dev Biol* 142: 129–137
- Araki I, Satoh N (1996) *cis*-Regulatory elements conserved in the proximal promoter region of an ascidian embryonic muscle myosin heavy-chain gene. *Dev Genes Evol* 206: 54–63
- Ausubel FM, Brenet R, Kingston RE, Moore DD, Seidman JG, Smith JA, Struhl K (1987) Current protocols in molecular biology. John Wiley and Sons, New York
- Cebria F, Nakazawa M, Mineta K, Ikeo K, Gojbori T, Agata K (2002) Dissecting planarian central nervous system regeneration by the expression of neural-specific genes. *Development Differ* 44: 135–146
- Chen CA, Manning DR (2001) Regulation of G proteins by covalent modification. *Oncogene* 20: 1643–1652
- Corbo JC, Gregorio AD, Levine M (2001) The ascidian as a model

- organism in developmental and evolutionary biology. *Cell* 106: 535–538
- Corbo JC, Levine M, Zeller RW (1997) Characterization of a notochord-specific enhancer from the *Brachyury* promoter region of the ascidian, *Ciona intestinalis*. *Development* 124: 589–602
- Davis LG, Dibner MD, Battey JF (1986) *Methods in Molecular Biology*. Elsevier Science Publishing, New York.
- Dever TE, Glynnias MJ, Merrick WC (1987) GTP-binding domain: Three consensus sequence elements with distinct spacing. *Proc Natl Acad Sci USA* 84: 1814–1818
- Fox CA, Sheets MD, Wickens MP (1989) Poly(A) addition during maturation of frog oocytes: distinct nuclear and cytoplasmic activities and regulation by the sequence UUUUUUAU. *Gene Dev* 3: 2151–2162
- Gilchrist A, Li A, Hamm HE (2002) G α COOH-terminal mini-gene vectors dissect heterotrimeric G protein signaling. *Sci STKE* 118: PL1
- Gupta SK, Gallego C, Lowndes JM, Pleiman CM, Sable C, Eisfelder BJ, Johnson GL (1992) Analysis of the fibroblast transformation potential of GTPase-deficient *gip2* oncogenes. *J Mole Cell Biol* 12: 190–197
- Hamm HE (1998) The many faces of G protein signaling. *J Biol Chem* 273: 669–672
- Hamm HE, Deretic D, Arendt A, Hargrave PA, Koenig B, Hofmann KP (1988) Site of G protein binding to rhodopsin mapped with synthetic peptides from the α subunit. *Science* 241: 832–835
- Hamm HE, Gilchrist A (1996) Heterotrimeric G proteins. *Curr Opin Cell Biol* 8: 189–196
- Harada R, Berube G, Tamplin OJ, Denis-Larose C, Nepveu A (1995) DNA-binding specificity of the cut repeats from the human cut-like protein. *Mol Cell Biol* 15: 129–140
- Heinemeyer T, Chen X, Karas H, Kel AE, Kel OV, Liebich I, Meinhardt T, Reuter I, Schacherer F, Wingender E (1999) Expanding the TRANSFAC database towards an expert system of regulatory molecular mechanisms. *Nucleic Acids Res* 27: 318–322
- Huelsken J, Birchmeier W (2001) New aspects of Wnt signaling pathways in higher vertebrates. *Curr Opin Genet Dev* 11: 547–553
- Imai K, Takada N, Satoh N, Satou Y (2000) β -catenin mediates the specification of endoderm cells in ascidian embryos. *Development* 127: 3009–3020
- Iwasa T, Kanehara K, Watari A, Ohkuma M, Nakagawa M, Tsuda M (2001) Heterotrimeric G protein α and β subunit genes of the ascidian, *Halocynthia roretzi*. In "Biology of Ascidians" Ed by H Sawada, H Yokosawa, CC Lambert, Springer-Verlag Tokyo, pp 147–152
- Iwasa T, Yanai T, Nakagawa M, Kikkawa S, Obata S, Usukura J, Tsuda M (2000) G protein α subunit genes in octopus photoreceptor cells. *Zool Sci* 17: 711–716
- Jeffery WR (2001) Determinants of cell and positional fate in ascidian embryos. *Int Rev Cytol* 203: 3–62
- Kim GJ, Nishida H (1999) Suppression of muscle fate by cellular interaction is required for mesenchyme formation during ascidian embryogenesis. *Dev Biol* 214: 9–22
- Kuehl M, Sheldahl LC, Park M, Miller JR, Moon RT (2000) The Wnt/Ca²⁺ pathway. *Trends Genet* 16: 279–283
- Liu T, DeCostanzo AJ, Liu X, Wang H-y, Hallagan S, Moon RT, Malbon CC (2001) G protein signaling from activated rat Frizzled-1 to the β -catenin-Lef-Tcf pathway. *Science* 292: 1718–1722
- Mazzoni MR, Hamm HE (1993) Tryptophan207 is involved in the GTP-dependent conformational switch in the α subunit of the G protein transducin: chymotryptic digestion patterns of the GTP γ S and GDP-bound forms. *J Prot Chem* 12: 215–221
- Meinertzhagen IA, Okamura Y (2001) The larval ascidian nervous system: the chordate brain from its small beginnings. *Trends Neurosci* 24: 401–410
- Meyers S, Downing JR, Hiebert SW (1993) Identification of AML-1 and the (8;21) translocation protein (AML-1/ETO) as sequence-specific DNA-binding proteins: the runt homology domain is required for DNA binding and protein-protein interactions. *Mol Cell Biol* 13: 6336–6345
- Nakagawa M, Miyamoto T, Ohkuma M, Tsuda M (1999) Action spectrum for the photophobic response of *Ciona intestinalis* (Ascidacea, Urochordata) larvae implicates retinal protein. *Photochem Photobiol* 70: 359–362
- Nicol D, Meinertzhagen IA (1988) Development of the central nervous system of the larva of the ascidian, *Ciona intestinalis* L. II. Neural plate morphogenesis and cell lineages during neurulation. *Dev Biol* 130: 721–736
- Nishida H (1986) Cell division pattern during gastrulation of the ascidian, *Halocynthia roretzi*. *Dev Growth Differ* 28: 191–201
- Nishida H (1987) Cell lineage analysis in ascidian embryos by intracellular injection of a tracer enzyme. III. Up to the tissue restricted stage. *Dev Biol* 121: 526–541
- Nishida H (2002) Specification of developmental fates in ascidian embryos: molecular approach to maternal determinants and signaling molecules. *Int Rev Cytol* 217: 227–276
- Nishimura S, Kandori H, Maeda A (1998) Interaction between photoactivated rhodopsin and the C-terminal peptide of transducin α -subunit studied by FTIR spectroscopy. *Biochemistry* 37: 15816–15824
- Otte AP, McGrew LL, Olate J, Anthanson NM, Moon RT (1992) Expression and potential functions of G-protein α subunits in embryos of *Xenopus laevis*. *Development* 116: 141–146
- Saitou N, Nei M (1987) The neighbor-joining method: a new method for reconstructing phylogenetic trees. *Mol Biol Evol* 4: 406–425
- Satoh N (1994) *Developmental Biology of Ascidians*. Cambridge University Press, New York
- Satoh N (2001) Ascidian embryos as a model system to analyze expression and function of developmental genes. *Differentiation* 68: 1–12
- Satoh N, Jeffery WR (1995) Chasing tails in ascidians: Developmental insights into the origin and evolution of chordates. *Trends Genet* 11: 354–359
- Satou Y, Imai KS, Satoh N (2001) Early embryonic expression of a LIM-homeobox gene *Cs-lhx3* is downstream of beta-catenin and responsible for the endoderm differentiation in *Ciona savignyi* embryos. *Development* 128: 3559–3570
- Satou Y, Takatori N, Fujiwara S, Nishikata T, Saiga H, Kusakabe T, Shin-i T, Kohara Y, Satoh N (2002) *Ciona intestinalis* cDNA projects: expressed sequence tag analyses and gene expression profiles during embryogenesis. *Gene* 287: 83–96
- Takahashi H, Mitani Y, Satoh G, Satoh N (1999) Evolutionary alterations of the minimal promoter for notochord-specific *Brachyury* expression in ascidian embryos. *Development* 126: 3725–3734
- Wilkie TM (2000) G-protein signaling: satisfying the basic necessities of life. *Curr Biol* 10: R853–R856
- Wolfgang WJ, Quan F, Thambi N, Forte M (1991) Restricted spatial and temporal expression of G-protein α subunits during *Drosophila* embryogenesis. *Development* 113: 527–538
- Wu C, Zeng Q, Blumer KJ, Muslin AJ (2000) RGS proteins inhibit Xwnt-8 signaling in *Xenopus* embryonic development. *Development* 127: 2773–2784
- Yasuo H, Satoh N (1994) An ascidian homolog of the mouse *Brachyury* (*T*) gene is expressed exclusively in the notochord cells at the fate restricted stage. *Dev Growth Differ* 36: 9–18

(Received October 18, 2002 / Accepted November 20, 2002)