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Effects of 17α-ethinyl estradiol exposure on estrogen receptors α and β and vitellogenins A, B and C mRNA expression in the liver of sand goby (Pomatoschistus minutus)

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Abstract

This study aims to characterize the estrogen receptor (er) in sand goby (Pomatoschistus minutus) and determine the temporal effects of 17α-ethinyl estradiol (EE2) on erα and vitellogenin (vtg) gene expression in males. Two partial cDNA sequences (erα and erβ1) are presented showing conserved structural features with ers of other species. Transcript levels for both ers were low in control fish but EE2 exposure (11 ng/L, for 29 days) increased both to a pattern similar to vitellogenic females. The relative expression of three vtg genes (vtga, vtgb and vtgc) along with erα was determined in control and male fish exposed to EE2 (11 ng/L) at multiple time-points over 29 days. All four transcripts were significantly induced due to exposure and expression rose during the time course with distinct temporal patterns and vtga reached a substantially higher level at the end of the time course coinciding with rapid elevation in erα expression.

1.1 Introduction

Estrogenic endocrine disruptors (EED) interact with the endocrine systems of animals by engaging with the estrogen signal transduction pathways, resulting in estrogenic toxicity with a myriad of detrimental and adverse effects (Hiramatsu et al., 2005). 17α-ethinyl estradiol (EE2) is a model EED and is found to contaminate European coastal waters with concentrations fluctuating as high as 125 ng/L (Pojana et al., 2004). The sand goby (Pomatoschistus minutus) is a small benthic fish that inhabits European coastal and estuarine environments. Sand goby have a one-year life cycle with distinctive well-characterized reproductive behaviours, for example sand goby males build nests into which females are lured to lay their eggs (Healey, 1971). In earlier works, sand goby has been utilized as a model in ecotoxicology for the study of endocrine disruption in both controlled exposure studies (Saaristo et al., 2009) and environmental monitoring (Kirby et al., 2003). Exposure of male and female animals to EE2 was shown to have adverse effects on reproductive output and mating behaviours (Robinson et al., 2003; Saaristo et al., 2010a, 2010b). The molecular mechanisms by which female egg production is impaired are poorly understood. In these studies it was difficult to contextualize the
apical endpoints with the classic molecular biomarkers of estrogenic exposure, such as expression of vitellogenin (vtg), partially because at that time, only a small fragment a single vtg was available. Recently this situation has been improved when three vtgs transcripts were identified and shown to be inducible by EE2 exposure in male sand goby (Humble et al., 2013). The three vtg complete cDNA sequences have now been fully sequenced (accession AGO64301.1 AGO64302.1 and AGO64303.1). Although male hepatic vtg is known to be inducible by exposure to EE2, the EED induced expression patterns of multiple vtg genes over time are unknown.

The er is central to the estrogen transduction pathway that is both crucial to vitellogenesis and EED mediated toxicity. Typically teleost fish have three subtypes of er (erα, erβ1 and erβ2) (Hawkins et al., 2000; Sabo-Attwood et al., 2004). erα is known to be up-regulated by high level EED exposure in male fish (Katsiadaki et al., 2002) and erβ1 is known to be inducible by injection of estradiol (Sabo-Attwood et al., 2004). However, the estrogen receptors (ers) have not been characterized in sand goby and it is uncertain if ers are suitable as biomarkers as their sensitivity to environmentally relevant concentrations of EED is questionable.

Our hypothesis is that sand goby possesses three er with conserved domain structures and exposure to environmentally relevant concentrations of EE2 induces time-dependent expression patterns in the hepatic expression of these er genes as well as in the multiple vtg genes already sequenced. A comparison of the temporal expression patterns of these estrogen sensitive genes will be useful for biomarker evaluation and risk assessment. The objectives are 1) to sequence multiple ers of the sand goby (at the mRNA and predicted protein level), categorize the ers by subtype and characterize the domain structures and evolutionarily conserved regions; 2) To quantify relative hepatic gene expression of ers in males EE2 exposure at environmentally relevant concentrations of EED and compare this to control females and control males; 3) characterize the temporal mRNA expression pattern of ers and vtgs throughout a long term exposure period to an EED enabling comparison of estrogen responsive genes to evaluate the sensitivity of these potential biomarkers.

2 Materials and Methods

2.1. The exposure scheme
The sand gobies used in the exposure experiments were caught using a hand trawl at natural breeding sites near the Tvärminne Zoological Station (University of Helsinki) on the southern coast of Finland. Trawling was conducted during the main breeding season (May-June). Only sexually mature fish were chosen to this study and they were separated by sex before introduction to the holding tanks. Fish were acclimated to the laboratory conditions for 2 weeks. From holding tanks fish were randomly assigned to six different exposure glass aquaria (80 x 80 x 40). Males were kept at a density of 45 males and females were kept at a density of 15 per tank. Tanks had a 3 cm layer of fine sand on the bottom and were equipped with a flow-through of seawater (see Saaristo et al., 2009, 2010a,b). Fish were fed twice a day during the exposure period.

The treatment was as follows: EE2 exposure (males), with nominal concentration of 20ng/L (measured concentration 11ng/L, standard deviation (SD) = 3.7, n = 10). During preparation of chemicals, EE2 (Sigma-Aldrich, Finland) powder was dissolved in acetone, which was evaporated using a stream of nitrogen thus eliminating the presence of solvent (Saaristo et al., 2010a,b). The EE2 concentration in the male exposure aquaria was measured by liquid chromatograph-mass spectrometer (LC-MS; HS 1100-Water Quattro II) using methods described in Saaristo et al., 2009). The study was approved by the Finnish National Board of Laboratory Animals.

2.2 Cloning of estrogen receptors

2.2.1 Targeting unknown sand goby er sequence

Deduced amino acid sequences for complete cDNAs of ers were sourced from the GenBank website for a variety of teleost species and aligned using CLUSTALW2 to identify conserved subtype-specific sequences (list of teleost species, protein IDs and accession numbers shown in Supplement 1). These were used to design the primers as follows: \( \text{er} \alpha \) forward primer (FP) 5’ ACCACTATGGGGTGTCGTC 3’ and reverse primer (RP) 5’ CATGCCTTTGCTGCTGT 3’, \( \text{er} \beta 1 \) FP 5’ GCTATGAAGTCGGCATGACC and RP 5’ GATCATGGCTTTGAGGAGA 3’ and \( \text{er} \beta 2 \) FP 5’ GTTGAGGCGTGAAGGCTGTC 3’ and reverse transcription polymerase chain reaction (RT-PCR).

2.2.2 RNA isolation and Reverse transcription
Total RNA was isolated from EE2 exposed male and control female liver tissue samples (100 mg) using NucleoSpin® RNA II kit (ABGene, Epsom, UK) following the manufacturer’s protocol and quantified by Nanodrop™ ND-1000 spectrophotometer. Superscript III reverse transcriptase (Invitrogen, Paisley, UK) was used to convert 2 µg RNA into cDNA, again according to the manufacturer’s instructions. The reverse transcription reactions were primed using random hexamers at a reaction concentration of 1.5 µM and oligo(dT) at a reaction concentration of 3 µM. The reaction was incubated at 50 °C for 60 min and then at 70 °C for 15 min. The cDNA was stored at -20 °C.

2.2.3 PCR amplification, cloning and sequencing

RTPCR was used to amplify er fragments from livers of EE2-exposed male and control female sand goby. Reddymix™ PCR Master Mix (1.1X) (Thermo Fisher Scientific., USA) was used with 0.2 µM reaction concentration for each primer and 1 µL sand goby cDNA and thermo-cycled following the manufacture’s recommendations. The PCR products were analysed by agarose gel electrophoresis (data not shown) and purified fragments were cloned into pJET1.2 vector and DH5α E. coli host using the CloneJET™ PCR cloning kit (Fermentas, UK) and the Subcloning Efficiency™ DH5α™ Competent Cells (Invitrogen, UK). Plasmids were purified from recombinant colonies (using GeneJET Plasmid Miniprep Kit, Fermentas, UK) and sequenced using GenomeLab™ Dye Terminator Cycle Sequencing with Quick Start Kit (Beckman Coulter Inc., Fullerton, USA) and processed using Long Fast Read program 1 (LFR1), a standard setting for DNA sequencing. The sequences generated were pair aligned with er sequences from Micropogonias undulatus (era accession: AAG16713.1, erβ accession AAG16711.1 and ery AAG16712.1), Gambusia affinis (era accession BAF76770.1, erβ1 accession: BAF76771.1 and erβ2 accession: BAF76772.1), Acanthogobius flavimanus (era accession: BAF46102.1 erβ accession: BAF46103.1, Oryzias latipes (era accession BAA86925.1, erβ accession NM_001104702.1 and erβ2 accession NM_001128512.1) and Acanthopagrus schlegelii (era accession AY074780.1, accession erβ AY074779.1 and erβ2 accession EU346949).

2.3 Quantification of Transcripts by Relative RT-qPCR.

RNA extraction from sand goby liver as described in section 2.2.2.
2.3.2 qPCR assays

The qPCR reactions were primed with transcript-specific primers. Primers for vtga, vtgb, vtgc and 28S ribosomal RNA (rs28) were presented previously (Humble et al., 2013). Primers for erα and erβ1 were designed using Primer3 (Rozen and Skaletsky, 2000) and primer pairs were screened against potential to form secondary structures using Netprimer (Premier Biosoft 2002). The reverse transcription, quantitative, PCR (RT-qPCR) primers were validated using end-point RT-PCR to amplify cDNA from female control fish (data not shown) to demonstrate single fragments of expected size and RT-qPCR standard curves constructed to assess the efficiency for each primer set (Table 1). rs28 shows little variation in hepatic expression in different genders or response to EE2 when a fixed amount of RNA is used (CT standard deviation ±0.55) was therefore used as reference gene. All RT-qPCR reactions were carried out in triplicate in 96 clear-well plates using Platinum® SYBR® green qPCR Supermix-UDG (Invitrogen, Paisley, UK) as previously described (Humble et al., 2013). After amplification a melting curve analysis (60 °C to 95 °C) was completed for each reaction to demonstrate a single product melting at the correct temperature.

2.4 Mathematical and statistical analysis of RTqPCR data

The RTqPCR mathematical calculation was performed separately for each target gene. First, the mean CT values for each gene (target gene and reference gene) and each biological sample was calculated using the three technical replicates. Second, a relative expression ratio (R) was generated for the gene of interest (relative to the reference gene) for each individual biological sample using the following equation presented by Pfaffl (2001) \( R = \frac{(E_{\text{target}})^{\Delta \text{CT}_{\text{target}}(\text{control-sample})}}{(E_{\text{ref}})^{\Delta \text{CT}_{\text{ref}}(\text{control-sample})}} \) with reference to assay efficiencies (E) to compensate for inter-assay efficiency variation. RS28 was used as reference gene (ref) and the mean of the control samples was used as “control”. Third, the R values were Log10 transformed to fit approximately normal distributions as determined by Shapiro-Wilk test and show homogeneity of variance as determined by Levene’s test.

Statistically significant differences in mRNA expression between control and exposed (or male and control female) samples were tested using Student’s unpaired t-test. For each gene of interest, significant differences between time points were calculated using one-way ANOVA with Tukey’s HSD post-hoc test. Between target gene comparisons were made using MANOVA with Tukey’s HSD post-hoc test. All statistical analyses were performed using the SPSS package (IBM SPSS Statistics 19).
3. Results

3.1. Partial sequencing of two estrogen receptors in sand goby

RT-PCR products of anticipated size were produced for a putative erα and erβ1 from EE2-exposed male and control female sand goby liver, but no product for erβ2 was formed even after using alternative tissues and primers (data not shown). The PCR products were cloned and sequenced resulting in contigs 977 bp (erα) and 600 bp (erβ1) in length that were used as queries for BLASTx search and showed highest homology to erα (accession: BAF46102.1, E-value: \(8 \times 10^{-121}\)) and erβ (accession: BAF46103.1, E-value: \(7 \times 10^{-120}\)) of Japanese common goby (Acanthogobius flavidus). The erβ of the Japanese common goby has not been categorized as subtype erβ1 or erβ2 yet the sand goby cDNA fragment has high similarity with erβ1 of other species (such as estrogen receptor beta1, partial [Acanthopagrus latus] accession: gb|AEX68678.1) to suggest this novel sand goby fragment is subtype erβ1.

To confirm the identity of the cDNA fragments, the sequences were translated, to generate 325 aa for erα and 200 aa for erβ1, and pair-aligned using water alignment with full length protein sequences of ers from other teleosts species (Micropogonias undulatus, Gambusia affinis, Acanthogobius flavidus, Oryzias latipes and Acanthopagrus schlegeli). Sand goby erα (accession: KC782769) showed highest identity with Japanese common goby erα (90.2%) while sand goby erβ1 (accession: KC782770) shows greatest homology with erβ of the Japanese common goby (89.4%). The partial sand goby erα and erβ1 deduced protein sequences pair-alignments with full length Japanese common goby erα and erβ protein sequence are shown in Fig. 1A and Fig. 1B respectively.

For erα, the sand goby sequence covers 60 amino acids (aa) of the 76 aa-long DNA binding domain, all the hinge domain and 201 aa of the 238 aa ligand-binding domain. There was a 100% match for the DNA binding domain, a 61.5% match for the hinge domain and a 93.9% match for the ligand binding domain. For erβ1 the sand goby sequence covered 15 aa of the 79 aa-long DNA binding domain, (93.3% match), all of the 41 aa hinge domain, (65.9%), and covered 143 of the 238 aa-long ligand binding domain (95.8%).

3.2 EE2 induced male er gene expression compared with female
Primers (shown in Table 1) were designed for RT-qPCR to amplify fragments of 158 bp long for both sand goby era and erβ1. The endogenous mRNA levels of era and erβ1 in male and female sand goby were analyzed using RT-qPCR. Very low mRNA levels were found for both ers in control males (mean CT for era was 26.7 and for erβ1 was 25.2). Females had higher endogenous levels of era (mean CT: 20.02) than erβ1 (mean CT: 26.2).

Relative RT-qPCR was used to analyse the fold change in era mRNA in male sand goby exposed to 11 ng/L EE2 for 29 days to show a highly significant increase in era mRNA. A significant difference in era was found between control males and females but no significant difference was found between females and EE2 exposed males indicating this exposure induced hepatic era expression in males similar to that of females. A small but significant difference in erβ1 was found between control males and males exposed to EE2 but no significant difference was found comparing control males with females.

3.3 Vtg-a, -b, -c & era expression over a month-long exposure to EE2

Relative RT-qPCR was used to analyse vtga, vtgb, vtgc and era mRNA levels in control and EE2-exposed (11 ng/L) male sand goby liver at 6 time points throughout 29 days (Fig. 3). Unexposed males had very low levels of mRNA for era and all vtg subtypes throughout the 29 day exposure period. This was detectable by highly significantly, lower CT values compared with non-template control (NTC). For instance, the mean CT values for the unexposed males at day 29 were 26.7, 29.4, 29.9 and 26.7 for vtga, vtgb, vtgc and era respectively while the respective NTC values were undetermined, 35.1, 36.4, 38.2 and 37.9 for the respective genes.

Samples from exposed males had a highly significant (p < 0.0001) increase in levels of vtg-a –b and -c mRNA expression compared with controls at all time-points measured. On the other hand, era showed significant differences (p < 0.05) at day 13 and 16, very significant differences at day 8, 24 and 29 (p < 0.01) but no significant difference at day 20 when comparing exposed and control samples.

Expression of mRNA in males exposed to 11 ng/L over 29 days EE2 relative to controls was used for comparison of multiple time-points to show increases in expression ratios for vtg-a, -b, -c and era.
and reveal distinct temporal and transcript specific changes in mRNA upregulation. For \textit{vtga}, there was a sharp rise at the beginning of the time course shown by a statistically significant increase between day 8 and all other time points. Day 29 was also significantly greater than day 8, 13, 16 and 24 showing that \textit{vtga} continued to rise at the later stages. \textit{Vtgb} on the other hand showed no significant difference between day 8 and day 13, 16 or 20 but here was a difference between day 8 and day 24 or 29. \textit{Vtgb} expression reached a plateau indicated by a lack of statistically significant differences between day 16, 20, 24 and 29. For \textit{vtgc}, day 8 was found to be significantly different from all other time points measured. Day 29 was found to be significantly higher than day 8, 13 and 16, but not significantly different to day 20 or 24. For \textit{era} there was a significant difference between day 29 and days 8, 13 or 20 however there was no significant difference comparing day 13 or day 20 with any other time point.

A comparison was also carried out between relative mRNA expression levels of \textit{vtg} target genes over the time course. At day 8 of exposure the relative expression levels of the \textit{vtgs} was in the order \textit{vtga} > \textit{vtgc} > \textit{vtgb} (ratio of relative gene expression \textit{vtga} : \textit{vtgc} : \textit{vtgb}, for exposed male 1.53 : 1.13 : 1) though this was found not to be significantly different. However at day 29 there was a significant difference (with \textit{vtga} > \textit{vtgc} > \textit{vtgb}) and the respective abundance ratio for \textit{vtga} : \textit{vtgc} : \textit{vtgb} was 6.94 : 2.34 : 1 indicating a divergence in the expression profiles for these three genes over time.

\textbf{4. Discussion}

\textbf{4.1 Analysis of novel \textit{era} and \textit{er}\textbeta 1 sequences}

We successfully cloned and sequenced two cDNA fragments from liver of sand goby which show high homology to \textit{era} and \textit{er}\textbeta 1 in other fish species. These sequences were translated to gain partial deduced protein sequences which were aligned with Japanese common goby (\textit{Acanthogobius flavimanus}) deduced proteins to show they had higher similarity at the DNA binding domains and ligand domains than the hinge domains. This is consistent with the functional roles of these domains reportedly conserved during evolution (Aranda and Pascual, 2001). Ray-finned fish (Actinopterygii) contain multiple \textit{ers} due to gene and genome duplication. Typically there are three \textit{er} genes in teleosts as described in the Atlantic croaker (\textit{Micropogonias undulates}) and largemouth bass
(Micropterus salmoides) (Hawkins et al., 2000; Sabo-Attwood et al., 2004). It is possible that our efforts to clone \( \text{er}\beta 2 \) failed for technical reasons but it is of interest that only two \( \text{er}s \) (\( \alpha \) and \( \beta \)) are found in the closely related Japanese common goby (Ito et al., 2007). Phylogenetic analysis suggests that \( \text{er}\beta 1 \) and \( \text{er}\beta 2 \) are the result of duplication in an ancestor that was shared with higher vertebrates in which only a single \( \text{er}\beta \) is present (Nelson and Habibi, 2013). It is unlikely that the goby lineage were not subject to the same duplication event considering \( \text{er}\beta \) of mammals shares more identities with \( \text{er}\beta 2 \) of fish than with \( \text{er}\beta 1 \) (Hawkins and Thomas, 2004). It is more likely that \( \text{er}\beta 2 \) was redundant and was lost in the goby lineage and all \( \text{er}\beta \) functions are maintained by \( \text{er}\beta 1 \). Phylogenetic analysis of VTGs also suggests a distinct evolutionary pathway in the gobies compared to other ray-finned fish (Thacker, 2009).

4.2 Expression of estrogen receptor genes

Our study shows that the sand goby has gender-specific patterns of hepatic \( \text{er} \) expression and by comparison, transcript levels of both \( \text{er}s \) were low in male with \( \text{er}\beta 1 \) marginally higher than that of \( \text{er}\alpha \). In contrast \( \text{er}s \) are reported as absent from the liver of male Japanese common goby but this may be the consequence of an insensitive end-point PCR technique used in that investigation (Ito et al., 2007). Work on zebrafish (Danio rerio) has indicated that endogenous levels of \( \text{er}\beta 1 \) are higher than that of \( \text{er}\alpha \) or \( \text{er}\beta 2 \) (Menuet et al., 2004) but it was unclear which gender of fish were used in that study. Meng et al., (2010) reported gender differences in \( \text{er} \) transcript levels in zebrafish liver with \( \text{er}\alpha \) and \( \text{er}\beta 2 \) in females being at higher levels than \( \text{er}\beta 1 \) while in males \( \text{er}\beta 1 \) and \( \text{er}\alpha \) were observed at very low levels and \( \text{er}\beta 2 \) was higher. The results reported here indicate that sand goby is similar to zebrafish in respect of gender differences in hepatic expression of \( \text{er}\alpha \) and \( \text{er}\beta 1 \) but differ because in sand goby, no \( \text{er}\beta 2 \) has been found.

In this study we demonstrated a marked increase in transcripts for \( \text{er}\alpha \), up to levels comparable to those seen in mature females, and a modest increase in \( \text{er}\beta 1 \) in response to EE2 exposure. Exposure of male Japanese common goby to xeno-estrogens has been reported to result in the induced hepatic expression of estrogen-dependent genes implying the presence of \( \text{er}s \) (Ohkubo et al., 2004). Here, temporal variation in transcription for \( \text{er}\alpha \) in male liver was studied over a 29 day EE2 exposure, and a very significant increase in \( \text{er}\alpha \) relative to the control group was seen at day 24 and expression continued to rise at day 29. This observation promotes the idea that \( \text{er}\alpha \) may be a suitable biomarker.
for EED exposure-monitoring in male sand goby with high mRNA levels in particular signaling prolonged EED exposure. In zebrafish short term exposure (48 hours) to 17β-oestradiol has been reported to cause disparate effects upon the hepatic transcript levels of the er, with erα increasing erβ1 decreasing (Menuet et al., 2002), which suggests zebrafish is dissimilar to sand goby regarding its downregulation of erβ1 in response to estrogens. The results reported here show similarity with those reported in largemouth bass where the three er subtypes are classified as α, β (erβ2) and γ (erβ1). Sand goby β1 showed greatest similarity to largemouth bass γ type. Similar to the sand goby, the liver of largemouth bass females has higher endogenous levels of erα than erγ, and the injection of males with E2 causes a large increase in erα and a moderate increase in erγ (Sabo-Attwood et al., 2004). The increase in erα expression found in EED exposed sand goby may act as a positive feedback, compounding the feminization process and further sensitizing the males to estrogen exposure. Here we have for the first time in a teleost species demonstrated the induction of erα and erβ1 by exposure to environmentally relevant concentrations of EED.

4.3 Expression of vitellogenin genes

The determination of complete sequences for three VTGs (accessions: JQ511252.1, JQ511253.1 and JQ51254.1) and the development of vtg type specific RT-qPCR assays (Humble et al., 2013) opened the door for a study of the temporal effects of EE2 on the abundance of these transcripts. Low levels of transcripts for all of the vtg types were found in liver of non-exposed males, arguably the result of low level exposure to an estrogenic chemical during the maintenance and treatment periods. We can discount that these low vtg levels in males were caused by EE2 since in control tanks EE2 was below detection level by LC-MS-MS quantification (Saaristo et al., 2010a). Other researchers have also found basal level of VTG mRNA in untreated males in Murray rainbowfish (Melanotonia fluviatilis) (Woods and Kumar, 2011) Japanese medaka (Oryzias latipes) (Sun et al., 2011) and zebrafish (Söffker et al., 2012). Endogenous male estrogen synthesis is essential for testicular development and sperm formation in vertebrates including fish (Schulz et al., 2010) thus could be responsible for basal vtg mRNA expression. However, other factors such as hypoxia and parasite infection are also known to stimulate vitellogenin expression in males (Murphy et al., 2009).

Exposure of male sand goby to EE2 (11 ng/L) resulted in large increases of each vtg type with vtga > vtgc > vtgb at all-time points although the differences in gene expression were only found to be
significant at day 29. Considering a significant difference between the relative levels of \( vtga, vtgb \) and \( vtgc \) was only found at later time-points of the EE2 exposure, statistical comparison of the hepatic expression of these \( vtg \) genes may be used as an indicator for the duration of estrogen contamination of coastal environments prior to sampling thus providing information useful to risk assessment in marine ecotoxicology.

At early time-points the level of each transcript was similar to that seen in vitellogenic females (Humble et al., 2013). In many other fish species induction of \( vtg \) mRNA and protein is observed with LOECs for EE2 in the range 5-10 ng/L suggesting that the sand goby is as sensitive to estrogenic endocrine disruption as the other species investigated (Woods and Kumar, (2011)). However, clear temporal differences between \( vtg \) types became apparent after 20 days of exposure with \( vtgb \) reaching a plateau while the rate of increase for \( vtgc \) slowed and \( vtga \) continued to increase. It is notable that the continued increase in \( vtga \) occurs at the same time that \( er \alpha \) increases markedly. This makes it plausible that the EED-induced temporal rise of \( er \alpha \) promotes a continued increase in \( vtg \) expression. Future work will test this hypothesis by cloning the promoter regions of \( vtg \) genes and studying their \( er \alpha \)-dependent control of transcription.

Future work will also apply these assays to study the natural seasonal variation in the production of multiple \( vtg \)s in females and the effects that EEDs on vitellogenesis. It is conceivable that the normal pattern of \( vtg \) production in females is altered by such exposure and that this may not produce an optimum balance of nutrient for embryonic development.

### 4.4 Conclusions

Unlike the situation in many other teleosts only two \( ers \) are evident in the sand goby. Both can be induced in males by EE2 exposure, a consequence of which might be to exacerbate the adverse effects of EED exposure. Supporting evidence is provided by the observation that the temporal increase in \( er \) expression occurs coincidentally with an increase in expression of \( vtga, vtgb \) and \( vtgc \) with \( vtga \) demonstrating the greatest temporal and total increase. The temporal change in \( er \alpha \) and \( vtgs \) transcript abundance reveals variation in the sensitivity of each of these potential biomarkers which is helpful for assessing their potential as biomarkers. The significant difference between the
abundance of all three vtgs only occurred after 29 days of exposure and may be considered an indicator of prolonged exposure.

5. Acknowledgement.

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6. References


Legends to Figures

Fig. 1. Alignment of sand goby partial protein sequences with full length protein sequences of Japanese goby \textit{era} (A) and \textit{er\textbeta}1 (B) by ClustalW2. Green text represents the N-terminal domain, red text the DNA binding domain, yellow text the hinge domain and blue text the ligand binding domain. Numbers represent the amino acid residues, \text{-}=gap, \text{*} = fully conserved residue, \text{:} = strongly similar residue \text{=} weakly similar residue.

Fig. 2. Hepatic \textit{era} and \textit{er\textbeta}1 relative mRNA expression in livers of control female and EE2-treated male sand goby relative to control males determined by relative RTqPCR. EE2 treated males were exposed to EE2 at 11ng/L for 29 days. Numbers of individuals are as follows: control males \text{n} = 7, exposed males \text{n} = 7 and control females \text{n} = 8. Error bars represent standard error for the mean (SEM) and statistical significance between control males and control females or exposed males were determined by Student’s unpaired t-test test \text{**} = P < 0.01 \text{***} = P < 0.001.

Fig. 3. Temporal, hepatic \textit{vtga}, \textit{vtgb}, \textit{vtgc} and \textit{era} relative mRNA expression in EE2 exposed (11 ng/L) (solid line) and control (dashed line) male sand goby. Data represent mean expression values \text{±} SEM normalized using RS28 reference gene and relative to control fish sampled at each time point. Unpaired student t-test was used to test for significant difference between exposed and control samples \text{(*)} = p < 0.05; \text{**} = p < 0.01; \text{***} = p < 0.001). Separately for each gene of interest, one-way ANOVA with Tukey HSD post-hoc test was used to test for significant differences between time points in exposed samples, The same letter (a, b, c) indicate no significant difference between time points whereas different letters indicate significant differences \text{(p} < 0.05) between time points.
ERα _A._flavimanus      MYPEESRGSGGVATVDLGDYDTAPTAPLPHTSSSSTGYSAPLDVHGPPSDGSLQSL 60
ERα _P._minutus      -----------------------------------------------------------

ERα _A._flavimanus      GSGPNPLMFPSHPSHPPSHHYLETSTSPIYRSGVSTQOLSREEHNGAAEAER 120
ERα _P._minutus      -----------------------------------------------------------

ERα _A._flavimanus      VSESGTGVGPGFMEMAKETRFEKGDHYANSNGLYWDRCGAFFKRISIQGHNDYNGM 180
ERα _P._minutus      -----------------------------------------------------------

ERα _A._flavimanus      PATMQCTINDKRKSSCPQHRLKCEYSGVMKKGRKDFGRVHFRKDDKDKSKGSHP 240
ERα _P._minutus      -----------------------------------------------------------

ERα _A._flavimanus      KTAPPQDNNKHSSMAGGKAFVSGMSFDQVQLQLIQAAPFLCSRPQKLSNGYTEGNNM 300
ERα _P._minutus      KTAPIQD-KRQYVSSSGGQAKLSITGMSFDQVQLQLIQAAPFLCSRPQKLSNGYTEGNNM 365

ERα _A._flavimanus      SLLTSMADKELVHMIAWKPLGFLQSLHDQVLLLESSLWLELMISLWRIHCPGKLI 360
ERα _P._minutus      TLLTSMADKELVHMIAWKPLGFLQSLHDQVLLLESSLWLELMISLWRIHCPGKLI 425

ERα _A._flavimanus      FARQDILDRSEGCVEGMAEFDMWLLATASRFMLKLRPEFICLKAILPNSQAFSFC 420
ERα _P._minutus      FAQQDILDRESDGCVEGMAEFDMWLLATASRFMLKLRPEFICLKAILPNSQAFSFC 485

ERα _A._flavimanus      GTMEPLHDSAAVQNLDTDDALIIHISQGSQYASSVARQQLLLLLSHIRHMSNKGM 480
ERα _P._minutus      GTMEPLHDAAVQNLDTDDALIIHISQGSQYASSVARQQLLLLLSHIRHMSNKGM 545

ERα _A._flavimanus      HILYMKCKNKKVFLYDILMLEMLDAHHLHPPRTQASSLNNDSVYSGSSSLSDPRGTST 540
ERα _P._minutus      -----------------------------------------------------------

ERα _A._flavimanus      GGGKSSPSVLQFGGSPGNCWIA 564
ERα _P._minutus      -----------------------------------------------------------
B)

ERβ_P._minutus

ERβ_A._flavimanus

MAASPEKDFFLLQLQEVDDSRAASRLTPLGSSLPSAALSIAAPPICISPYPTELGFDPY 60

ERβ_P._minutus

ERβ_A._flavimanus

APLFYSSIFSYSNSTGLSECSTVNHQLPSLFNPWSHRVHGSSPLMHRQARPAHTQPTP 120

ERβ_P._minutus

ERβ_A._flavimanus

SPWVEIPRDSVLMCKRRRSQESDEAVVSSGKSDLHVCVHASICGHWGVCWSEGC 180

ERβ_P._minutus

ERβ_A._flavimanus

KAFYKSIQGNDYICPATQCTIDKRSKSCQACRLKCYEVGMTKCMKRGKERGLRSP 240

ERβ_P._minutus

ERβ_A._flavimanus

QASRRMTRLSTQGRGASRVLPSVVPFPEWHPTLTFQPQLIQRIMAAEPEYILKDM 81

ERβ_P._minutus

ERβ_A._flavimanus

QASRRRTRLSSQRSTGAKLPPVP-VVFRFEPQFALSPEQLIGRIEAPPEYILKDM 299

ERβ_P._minutus

ERβ_A._flavimanus

KRPLTEANVMSSMSLNASKELWMTWAKIPGFVDSLGLQVHLCECGWLMG 141

ERβ_P._minutus

ERβ_A._flavimanus

KRPLTEANVMSSMSLNASKELWMTWAKIPGFVDSLGLQVHLCECGWLMG 359

ERβ_P._minutus

ERβ_A._flavimanus

RSVEHPKLIFSPLLSRREEGSCVGFVEIFDMVAATSREVRLKHQREEVYCLAMA 200

ERβ_P._minutus

ERβ_A._flavimanus

RSVDHPKLIFSPLLSRREEGSCVGFVEIFDMVLAATSREVRLKHQREEYVCLAMIL 419

ERβ_P._minutus

ERβ_A._flavimanus

LNSHNCSSSEGSEEVQSRKLLLCLLDVTDALWAAIKGTLSSFRQQYTRLALMLSH 479

ERβ_P._minutus

ERβ_A._flavimanus

IRHASNKGMDHJHCMEKMNMTPLVYDDLMALDIAHMNSRLFCRPTQEQEPDPMEQERP 539

ERβ_P._minutus

ERβ_A._flavimanus

HISPSGSNTCPSDENQPSETIKTPQ 567

Fig 1
**era**

**Relative mRNA expression**

- **Control male (n=7)**
- **Exposed male (n=7)**
- **Control female (n=8)**

**Significance:**
- ***p < 0.001**
**er81**

![Bar chart showing relative mRNA expression of er81 in control male (n=7), exposed male (n=7), and control female (n=8) groups. The chart indicates a significant difference (*) between the control female and the other groups.](chart.png)

Fig 2