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Research Article

A rapid approach to assess estrogenic transcriptional activity of bisphenol A in the liver of goldfish

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Abstract

Bisphenol A (BPA) is a synthetic compound widely used in types of consumer goods and medical tools. It has been shown that BPA acts as an endocrine disruptor chemical casuing negative impact on reproductive functions. The present study used an *in vitro* approach to assess estrogenic transcriptional activity of BPA as a rapid and sensitive method. The cultured pieces of hepatic tissue of goldfish (*Carassius auratus*) were exposed to 1, 5, 25 μ g L⁻¹ BPA and 1 μ g L⁻¹ E₂ for comparison over 24 h. Compared to control, the mRNA transcript of $er\beta$ -II showed a significant increase in the hepatic tissues exposed to all doses of BPA and E₂. The mRNA transcript of $er\beta$ -II was signifineantly increased in hepatic tissues exposed to 1 and 5 μ g L⁻¹ BPA and E₂. The mRNA transcripts of vtg in the hepatic tissues treated with 5 μ g L⁻¹ BPA and E₂ were also increased, significantly. Finally, cyp1a mRNA transcript showed a significant increase in the hepatic tissues exposed to 5 and 25 μ g L⁻¹ BPA and E₂. These results show an estrogenic activity of BPA similar to E₂, and suggest that *in vitro* approach can be used as an alternative to *in vivo* test to detect estrogenic effects of BPA.

Keywords: BPA, Esterogenic activity, Vitellogenin, mRNA transcript

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Introduction

Bisphenol A (BPA) is synthesized by catalyzed condensation of acetone and phenol (Prokop et al., 2004). It is highly produced and used as a precursor of plastics for consumer goods (including food-packaging materials, surface coatings, and toys) and medical tools (including heart-lung machines. incubators, hemodialyzers, and dental sealants and fillers) (Liao and Kannan, 2011; Huang et al., 2012; Liao et al., 2012).

Exposure to BPA is linked to a wide range of health problems including reproductive impairments such testicular dysgenesis syndrome, hormonal disorders, follicular loose, cryptorchidism, and diminished gamete quality in males and females, which may result in decreasing fertility (Richter et al., 2007; Rochester 2013; Kundakovic et al., 2013; Zhou et al., addition. **BPA-caused** 2016). In reproductive impairments which could be transgenerationally transmitted by epigenetic mechanisms (Dolinoy et al., 2007; Prins *et al.*, 2008; Abdel-Maksoud et al., 2015; Kumar and Thakur, 2017; Bansal et al., 2019).

In the aquatic environments, BPA originates from BPA-based products, of landfill sites effluents and wastewater treatment plants, or natural degradation. The environmental concentrations of BPA have been frequenly measured which range from less than 1 µg/L to higher than 21 µg/L in hot spots (Belfroid et al., 2002; Wintgens et al., 2003; Gatidou et al., 2007; Staples *et al.*, 2018; Xu *et al.*, 2018). In fish, BPA has been also detected, for instance its concentration in the body of fish caught around Taiwan, the Gulf of Naples in Italy, and local market of Hongkong were measured to be 0.2-25.2 (Lee *et al.*, 2015), 0.5-6.0 (Mita *et al.*, 2011) and 0.8-19.3 mg kg⁻¹ (Wong *et al.*, 2017), respectively.

Similar to higher vertebrates, studies have shown that in vivo exposure of fish to BPA causes reproductive disorders. In males, BPA disrupts hormonal functions of the hypothalmouspitituary-testis (HPT) axis (Lindholst et al., 2000; Mandich et al., 2007), which results in diminished sperm quality (Lahnsteiner et al., 2005; Hatef et al., 2012a, b). However there are still questions that remain unanswered to identify the modes of action of BPA on reproductive system.

In vertebrates, estrogens are key regulatory hormones in development and functions of the reproductive system, their physiological and functions are transmitted to target cells by intracellular estrogen receptors (ERs) (Nilsson et al., 2001; Gustafsson, 2003; Heldring et al., 2007). In fish, 17β-estradiol (E₂) regulates vitellogenin (Vtg) synthesis in the liver, which is essential for the ovarian development in females (Hara et al., 2016). It has been well demonstrated that exposure to or with endogenous treatment or estrogens induces exogenous Vtg production mediated by ERs in males, which may cause an intersex (the presence of testis-ova) (Sumpter and Jobling, 1995; Wheeler *et al.*, 2005; Hutchinson *et al.*, 2006; Miyagawa *et al.*, 2014). Although, occurrence of intersex has been reported in fish exposed to BPA, *in vivo* (Metcalfe *et al.*, 2001; Mandich *et al.*, 2007), however there are controversies in the estrogenic-like activity of BPA. *In vitro* studies have revealed a weak binding affinity of BPA to ERs (Gould *et al.*, 1998; Kuiper *et al.*, 1998).

To better understand **BPA** estrogenic-like activity using an in vivo protocol, it needs to manipulate duration of exposure, use a large number of sample size, examine various concentrations of BPA, and control the developmental stages. Therefore, as the Organization for **Economic** and Cooperation Development (OECD) suggested (Lee et al., 2014), application of an in vitro protocol would be useful to control experimental condition, and run more tests with consideration to fish welfare. The aim of the present study was to investigate the estrogenic-like activity of BPA using an in vitro protocol. We examined the effects of different concentrations of BPA on transcriptional activity of vtg, erβ-I, and $er\beta$ -II as well as cytochrome p450 (cyp1a) in the cultured pieces of liver in goldfish (Carassius auratus). These genes are known powerful as biomarkers for estrogenic activity and toxicity of environmental contaminants (Hiramatsu et al., 2006; Kim et al., 2008; Søfteland et al., 2010). This study provides a simple, sensitive and high

throughput screening method to investigate potential of hormonal-like activity of environmental contaminants.

Materials and methods

Exposure and experimental design Experimental groups were composed of BPA (1, 5 and 25 μ g L⁻¹), E₂ (1 μ g L⁻¹), solvent control, and control. Bisphenol A and E2 were dissolved in EtOH (Sigma Aldrich). Twenty male and female goldfish (mean body mass of 32 g and total length of 8-12 cm) imported to the laboratory and maintained in flow-through tanks to acclimize for around 5 days. Water temperature was approximately 20°C kept and photoperiod was 12 h light/12 h dark. This study was carried out in strict accordance with the recommendations in the Guide for the Care, Protection and Use of Laboratory Animals of the Canadian Council and the Ministry of Health of the Czech Republic approved by the Ethics Committee of the University of Calgary Animal Care Committees and by the Central Ethics Committee of the Ministry Agriculture of the Czech Republic (§17, arti- cle 1 of the low 246/1992 Sb), respectively. All fish were antsthesized before being sacrified to minimize suffering.

The liver was collected from male goldfish (12 individuals), washed in fresh media, and cut by scalpel into 1–3 mm³ pieces for culturing. Under a sterile hood, the pieces were washed again for several times with culture medium solution (M199 with Hanks

salts and containing 100 U ml⁻¹ penicillin, 100 mg ml⁻¹ streptomycin; Gibco). The liver pieces were added in equal amounts (approximately 50 mg) to each well of a 12-well plate and a total of 4 mL of prepared culture media was added containing BPA or E2. All treatments were replicated in six separate experiments using different well preparations. Twenty-four h posttreatment, the media was discarded and the tissue pieces were collected in RNAse free Eppendorf tubes containing 1 mL Trizol Reagent (Invitrogen, Cat. No. 15596-018), and frozen at -80° C until use. Data of control without EtOH did not show any significant difference with those of solvent control (data are not shown). Therefore, only the data for solvent control were used as reference for comparison with respective treatments.

RNA extraction and complementary DNA (cDNA) synthesis

Tissue was homogenized in Trizol, and chloroform was added. After mixing, samples were centrifuged (12,000 g for 15 min) and supernatants were transferred into the new tubes containing equalvolume an of isopropanol. The mixture was centrifuged (12,000 g for 10 min), and the precipitated RNA was washed using mL EtOH 75%. Total **RNA** concentration was estimated from absorbance at 260 nm (A260 nm, Nanodrop, USA). The RNA quality was verified by A260 nm/A280 nm ratios between 1.8 and 2 and A230 nm/A260 nm ratios higher than 2.

The cDNA was synthesized from 4 ug of total RNA of each sample using Molonev Murine Leukemia Virus Reverse Transcriptase (M-MLV) (Invitrogen, Cat No. 28025-013) and oligo (dT)₁₈ primer (Promega, Madison, WI, USA) following the manufacturer's instructions. Two µl of oligo (dT)₁₈ primer (500 µg ml⁻¹) was added to each samples and the reaction mixture was heated to 70 °C for 10 min, and then quickly chilled to 4 °C. After cooling, 4 ul of 5× first-strand buffer, 2 ul DTT (100 mM), 0.4 ul dNTP (100 mM) (Cat. No. dNTP-01, UBI Life Science, Canada) and 0.7 ul M-MLV (200 U ul 1) and nuclease free water were added to a total volume of 18 µl. The reaction mixture was then incubated at 25 °C for 10 min and at 37 °C for 50 min using iQ cycler. The reaction was deactivated by heating at 70 °C for 15 min. A negative control was run for each sample. Each 18 µl reaction was diluted 3-fold in nuclease free water and used for quantitative real time PCR assay. iCycler iQ Real-time PCR Detection System (Bio-Rad Lab. Inc.) was used for studying mRNA levels with the following condition per reaction: 1 µl of diluted cDNA, 6.25 µM of each primer (0.26 µL of forward and reverse primers), 12.5 µl SYBR Green PCR Mix (Qiagen Master Mississauga, Canada) and ultrapure distilled water (Invitrogen) to a total volume of 25 µl. Primers for all genes were designed using NCBI tool Primer BLAST with reference the known goldfish to sequences. Primer efficiencies on serial dilutions of cDNA were all between 90% and 100%. Table 1 shows the sequences of specific primers used in this study. PCR was run in the following cycling conditions: initial denaturation at 95°C for 30 s, followed by 40 cycles of 5 s at 95°C, appropriate annealing temperatures for 31 s. The specificity of the amplified product in quantitative PCR the assay was determined by analyzing the melting curve to discriminate target amplicon from primer dimer or other non-specific products. A single melt curve was observed for each primer set in all quantitative **PCR** reactions. No amplification product also was observed in non-template controls as well as no primer-dimer formations. Each sample was run in triplicate and the mean threshold cycles (determined by the linear portion of the fluorescence absorbance curve) were used for the final calculation. The mRNA levels were normalized to the mRNA level of glyceraldehyde-3phosphate dehydrogenase (gapdh) using standard $2^{-\Delta\Delta Ct}$ method.

Table 1: Primer sequences and annealing temperature applied for studying alternations in mRNA transcript of selected genes using aRT-PCR in the present study.

transcript of selected genes using qX1-1 CX in the present study.				
Genes	Forward Primer	Reverse Primer	Annealing temperatur e (°C)	GenBank Accession
vtg	GAAGTGCGCATGGTGGCTTGTATT	AGCTGCCATATCAGGAGCAGTGAT	55	DQ641252
erβ - I	GGCAGGATGAGAACAAGTGG	GTAAATCTCGGGTGGCTCTG	55	AF061269
erβ - II	GGATTATTCACCACCGCACG	TTCGGACACAGGAGGATGAG	55	AF177465
cyp1a	TGCCCTTGAGGAGCACATCAGC	CGTCGTCGTGGCTGTAGCG	58	DQ517445
gapdh	TGATGCTGGTGCCCTGTATGTAGT	TGTCCTGGTTGACTCCCATCACAA	57	AY641443

Genes: vitellogenin (vtg), estrogen receptor subunit β -I (er β - I), estrogen receptor subunit β -II (er β - II), cytochrome p450 1a (cyp1a).

House keeping gene: glyceraldehyde 3-phosphate dehydrogenase (gapdh).

Statistical analyses

Homogeneity of variance and normal distribution of data were tested using Levene's and Kolmogorov–Smirnov's tests, respectively. As needed, data were transformed to meet assumptions of normality and homoscedasticity. Tukey–Kramer test was used in conjunction with an ANOVA to find which means are significantly different from another at each sampling time (alpha =0.05). In this context, data of

BPA treated groups were compared with solvent control. Similarly, E₂ treated group was compared with solvent control and with BPA treated groups. All data are presented as mean ± standard error of mean (SEM).

Results

Estrogen receptor β I (er β -I) mRNA transcript

The effects of BPA on $er\beta$ -I was evaluated in goldfish cultured liver

tissue by analysis of mRNA transcript of $er\beta$ -I after 24 h exposure to BPA and E₂. There was a significant increase in $er\beta$ -I mRNA level in cultured hepatic tissue treated with BPA concentrations,

which included 1 μ g L⁻¹ (3.47-fold), 5 μ g L⁻¹ (5.94-fold), 25 μ g L⁻¹ (3.89-fold) and also E₂ (5.05-fold) compared to the control (p<0.05, Fig. 1).

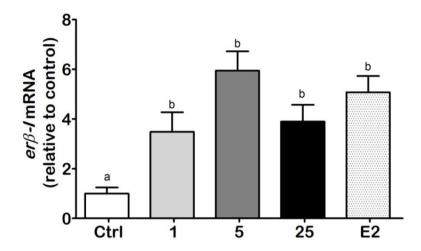


Figure 1: Alternations in the mRNA levels of estrogen receptor β-I (erβ-I in the hepatic tissue of male goldfish exposed to 1, 5 or 25 μg L⁻¹ bisphenol A (BPA) and 1 μg L⁻¹ 17β-estradiol (E₂), in vitro. Pieces of hepatic tissues were cultured in M119 culture media containing BPA, E₂, or ethanol as solvent. Alternations in transcriptional activity of er subtypes were studied using a quantitative real-time PCR following 24 h of exposure. Data are expressed as mean±SEM (n=6). Values with different superscripts are significantly different (p<0.05, ANOVA with Tukey's post hoc test).

Estrogen receptor β -II subtypes (er β -II) mRNA transcript

Following 24 h exposure, expression of $er\beta$ -II was significantly higher with a 3.61-fold, 5.02-fold and 3.14-fold increase in the hepatic tissue exposed to 1 and 5 µg L⁻¹ of BPA and to E₂, respectively (p<0.05, Fig. 2). However, the expression of $er\beta$ -II in hepatic tissue exposed to 25 µg L⁻¹ BPA remained unchanged compared to the control (p>0.05, Fig. 2).

Hepatic vitellogenin (vtg) mRNA

There was a significant 3.62-fold increase in vtg mRNA expression when the cultured hepatic tissue treated with 5 µg L⁻¹ BPA compared to the control. Moreover, the mRNA levels of vtg in the cultured hepatic tissue treated E₂ had significant 3.18-fold increase after 24 h exposure (p<0.05, Fig. 3). The mRNA level of vtg showed trends toward increases at 1 and 25 µg L⁻¹ BPA, however the differences were not significant compared to the control (p>0.05, Fig. 3).

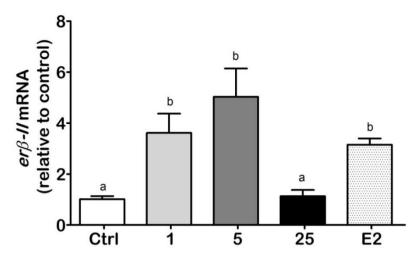


Figure 2: Alternations in the mRNA levels of estrogen receptor β-II (erβ-II) in the hepatic tissue of male goldfish exposed to 1, 5 or 25 μg L⁻¹ bisphenol A (BPA) and 1 μg L⁻¹ 17β-estradiol (E₂), in vitro. Pieces of hepatic tissues were cultured in M119 culture media containing BPA, E₂, or ethanol as solvent. Alternations in transcriptional activity of er subtypes were studied using a quantitative real-time PCR following 24 h of exposure. Data are expressed as mean±SEM (n=6). Values with different superscripts are significantly different (p<0.05, ANOVA with Tukey's post hoc test).

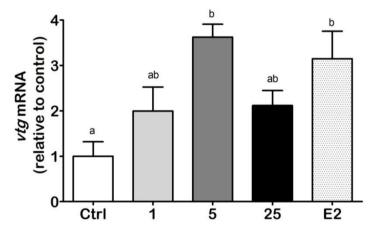


Figure 3: Alternations in the mRNA levels of vitellogenin (vtg) in the hepatic tissue of male goldfish exposed to 1, 5 or 25 μg L⁻¹ bisphenol A (BPA) and 1 μg L⁻¹ 17 β -estradiol (E₂), in vitro. Pieces of hepatic tissues were cultured in M119 culture media containing BPA, E₂, or ethanol as solvent. Alternations in transcriptional activity of vtg were studied using a quantitative real-time PCR following 24 h of exposure. Data are expressed as mean±SEM (n=6). Values with different superscripts are significantly different (p<0.05, ANOVA with Tukey's post hoc test).

Cytochrome p450 1A (cyp1a) mRNA Following 24 h exposure to BPA, cyp1a mRNA levels showed increases in a concentration manner, which were significant at 5 μg L⁻¹ (3.15-fold) and 25 μg L⁻¹ (3.57-fold) compared to the control. Moreover, there was a significant 2.36-fold increase in cyp1a mRNA levels of hepatic tissue after 24 h exposure to E_2 (p<0.05, Fig. 4).

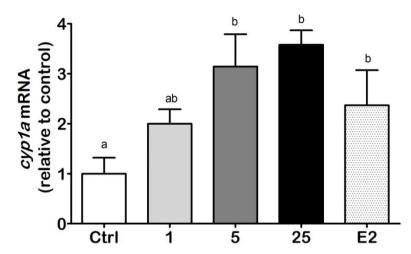


Figure 4: Alternations in the mRNA levels of cytochrome p450 1A (cyp1a) in the hepatic tissue of male goldfish exposed to 1, 5 or 25 μg L⁻¹ bisphenol A (BPA) and 1 μg/L μg L⁻¹ 17β-estradiol (E₂), in vitro. Pieces of hepatic tissues were cultured in M119 culture media containing BPA, E₂, or ethanol as solvent. Alternations in transcriptional activity of cyp1a were studied using a quantitative real-time PCR following 24 h of exposure. Data are expressed as mean±SEM (n=6). Values with different superscripts are significantly different (p<0.05, ANOVA with Tukey's post hoc test).

Discussion

We have previously reported that BPA is capble of disrupting transcriptional activities of genes that are involved in reproduction of goldfish following 30-90 days of exposure, in vivo (Hatef et al., 2012b). Briefly, our results have shown that BPA induces vtg mRNA in the liver mediated by stimulation in mRNA transcript of $er\beta$ subtypes and P450 aromatase. which converts androgens to estrogen. In the present study, we used an alternative, rapid and highly sensitive detection method to evaluate the estrogenic-like activity of BPA.

The present study showed that mRNA transcripts of *erβ-I* were increased in BPA treated hepatic tissue, which is consisted with previous studies that have used an *in vivo* approach (Huang *et al.*, 2010; Hatef *et al.*, 2012b). However, mRNA transcript of *erβ-II* was increased in hepatic tiusse exposed to 1 and 5 μg L⁻¹ BPA and E₂, but remained unchanged at 25 μg L⁻¹ BPA. These show that BPA effects on transcriptional activities of *er* subtypes

is different, and suggest that it might be contributed to affinity of BPA to *er* subtypes. Similarly, BPA-induced changes in transcriptional activity of *er* subtypes has been frequenly reported when fish were exposed to BPA, *in vivo* (Seo *et al.*, 2006; Huang *et al.*, 2010; Hatef *et al.*, 2012b; Miyagawa *et al.*, 2014).

In E₂ treated hepatic tiusse, either erβ-I or erβ-II mRNA levels were increased following 24 h of exposure, indicating estrogenic activity of E₂ is mediated by er subtypes (Kuiper et al., 1998; Liu et al., 2009; Nelson and Habibi, 2010). In BPA treated hepatic tissue, higher transcriptional activities of er subtypes were observed at 5 µg L BPA, represent inducing transcriptional activities of er subtypes required rather higher concentrations of BPA, compared to E_2 . This might be addressed to higher estroneic activity of E₂ (Gould et al., 1998; Li et al., 2015).

In males, the physiological Vtg level is very low and not properly detectable unless exposed to estrogen xenoestrogens. Therefore, observation of high levels of Vtg has been used as a marker of estrogenic-like contaminants (Sohoni et al., 2001; Mandich et al., 2007; Amaninejad et al., 2018). In the present study, we observed stimulation of vtg mRNA transcript of hepatic tissue exposed to 5 µg L⁻¹ and E_2 , which is consisted with alternations in mRNA levels of estrogen receptor subtypes. The latter suggests that BPAinduced vtg transcription is particularly mediated by $er\beta$ subtypes. In the present study, we did not assess the transcriptional activity of $er\alpha$ as our previous study have shown that mRNA level of this gene remained unchanged in the liver of goldfish exposed to BPA, in vivo (Hatef et al., 2012b). It is worth to note that several in vivo studies have the stimulation reported synthesis in the liver of fish exposed to BPA including goldfish (Hatef et al., 2012a), swordtail (Kwak et al., 2001), fathead minnow (Sohoni et al., 2001; Brian et al., 2005) medaka (Kamata et al., 2011), zebrafish (Muncke et al., 2007), and rainbow trout (Lindholst et al., 2000).

The cypla gene is one of the main members of the cytochrome p450 1a (cyp1) family, which is a detoxifying gene transcribed especially in the liver of fish (Olsvik et al., 2007) and has suggested as a sensetive biomarker for investigating xenobiotics and water pollutants (Kim et al., 2008; Søfteland et al., 2010). In the present study, we observed the elevation in mRNA transcript of cypla in cultured pieces of hepatic tissue exposed to BPA was consistent with previous study where exposure to BPA increased mRNA transcript of cypla in fathead minnows, in vivo (Zare et al., 2018). Modulation of hepatic cyp1a expression markedly affects the potential risks, which is important toxicologically (Williams et al., 1998).

In conclusion, our results show an estrogenic-like activity of BPA, and support our previous study in which BPA-induced Vtg synthesis via *er*

subtypes has been reported in goldfish, *in vivo*. This study provides valuable information for biologists to establish and use *in vitro* approach as an alternative tool to *in vivo* test to detect hormonal like activity of endocrine disrupting chemicals.

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