

Manuscript Number:

Title: Effect of 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD) on heme oxygenase-1, biliverdin IX α reductase and δ -aminolevulinic acid synthetase 1 in rats with wild-type or variant AH receptor

Article Type: Regular Article

Keywords: 2,3,7,8-tetrachlorodibenzo-p-dioxin; heme oxygenase; δ -aminolevulinic acid synthetase; biliverdin reductase; heme metabolism

Corresponding Author: MSc Marjo Niittynen, MSc

Corresponding Author's Institution: National Public Health Institute

First Author: Marjo Niittynen, MSc

Order of Authors: Marjo Niittynen, MSc; Jouni T Tuomisto, Dr.; Raimo Pohjanvirta, Prof.

Abstract: 2,3,7,8-Tetrachlorodibenzo-p-dioxin (TCDD) causes hepatic accumulation of biliverdin and its monoglucuronide in line B rats, but not in line A rats. They are both derived from crosses between TCDD-sensitive Long-Evans (Turku/AB; L-E) and TCDD-resistant Han/Wistar (Kuopio; H/W) rats. Line A is highly resistant to acute lethality of TCDD due to an H/W-like, altered AHR, while line B is moderately resistant due to H/W-type alleles of an unidentified gene. Since hepatic and splenic heme oxygenase-1 (HO-1), biliverdin IX α reductase (BVRA) and δ -aminolevulinic acid synthetase 1 (ALAS1) are key enzymes in heme metabolism, the effect of TCDD on them was studied at the levels of mRNA (all three enzymes), protein expression (HO-1), and enzymatic activity (BVRA, liver only). In both lines A and B, 300 μ g/kg TCDD transiently repressed hepatic HO-1 mRNA on day 2 but induced HO-1 protein expression at later time-points; however, the impact emerged earlier (day 14 vs. day 35) in line B rats. In spleen, TCDD repressed HO-1 mRNA and protein expression in lines A and B through days 2-35, but did not affect its mRNA levels in L-E rats (10 days after 100 μ g/kg). In all rat strains/lines, there was a strong repression of ALAS1 and a moderate induction of BVRA mRNA in liver, but mostly not in spleen. Hepatic BVRA activity was increased in lines A and B on day 14. At 5 weeks, it was still elevated in line A but only 51% of control in line B.

Induced hepatic heme degradation coupled with oxidative stress may underlie biliverdin accumulation in line B.

Editorial Office
Toxicology

Kuopio May 20, 2008

Dear Sir/Madam,

Please find enclosed our original manuscript entitled, "Effect of 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD) on heme oxygenase-1, biliverdin IX α reductase and δ -aminolevulinic acid synthetase 1 in rats with wild-type or variant AH receptor" by Marjo Niittynen, Jouni T. Tuomisto, and Raimo Pohjanvirta. We would like to submit this manuscript for consideration for publication in *Toxicology*. We have previously shown that TCDD induces accumulation of heme degradation product biliverdin in rat liver (*Toxicol. Sci.* 71, 2003). This is a unique phenomenon observed almost exclusively in so called line B rats, which originate from crosses between the most TCDD-sensitive and the most TCDD-resistant rat strains (Long-Evans [*Turku/AB*] and Han/Wistar [*Kuopio*], respectively). In the current study, we demonstrate that in rat liver, TCDD induces hepatic protein expression and catalytic activity of HO-1 and BVRA, the enzymes responsible for heme degradation, respectively. Thus, increased hepatic heme degradation may be one reason behind the biliverdin accumulation in line B rats. However, since the effects were similar also in rat strains in which biliverdin accumulation has never been observed, there must be additional factors in line B rats, such as severe oxidative stress or decreased secretion of bilirubin out of the hepatocyte, which are needed for the phenomenon to take place. In addition, hepatic ALAS1 mRNA expression was strongly repressed by TCDD in all studied rat strains. Simultaneous repression of ALAS1 and induction of HO-1 might be due to increased hepatic free heme level. These effects of TCDD on HO-1, BVRA and ALAS1 were mostly not observed in spleen; on the contrary, HO-1 was even repressed in that organ in two out of three studied rat strains, suggesting that the effects of TCDD on heme degradation are tissue-specific. An interesting detail is that there may be post-transcriptional stabilization involved in the regulation of HO-1 expression. Altogether, these findings shed more light on the little-studied phenomenon of hepatic biliverdin accumulation in response to TCDD exposure and have potential implications on the mechanisms of TCDD toxicity.

Thank you for your consideration.

Sincerely,
Marjo Niittynen

--

Marjo Niittynen
M.Sc., researcher
National Public Health Institute
Department of Environmental Health
P.O. Box 95
FI-70701 Kuopio, Finland
telephone: +358 17 201126
fax: +358 17 201265
e-mail: marjo.niittynen@ktl.fi

Conflict of interest statement: The authors declare that there are no conflicts of interest.

Effect of 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD) on heme oxygenase-1, biliverdin IX α reductase and δ -aminolevulinic acid synthetase 1 in rats with wild-type or variant AH receptor

Marjo Niittynen¹, Jouni T. Tuomisto¹ and Raimo Pohjanvirta^{2,3}

¹Department of Environmental Health, National Public Health Institute, Box 95, FI-70701 Kuopio, Finland

²Finnish Food Safety Authority EVIRA, Kuopio Research Unit, Box 92, FI-70701 Kuopio, Finland

³Department of Food and Environmental Hygiene, Faculty of Veterinary Medicine, Box 66, FI-00014 University of Helsinki, Finland

Correspondence to: Marjo Niittynen
National Public Health Institute
Department of Environmental Health
P.O. Box 95
FI-70701 Kuopio, Finland
telephone: +358 17 201126
fax: +358 17 201265
e-mail: marjo.niittynen@ktl.fi

E-mail addresses:
Marjo Niittynen marjo.niittynen@ktl.fi
Jouni T. Tuomisto jouni.tuomisto@ktl.fi
Raimo Pohjanvirta raimo.pohjanvirta@helsinki.fi

Key words: 2,3,7,8-tetrachlorodibenzo-*p*-dioxin; heme oxygenase; δ -aminolevulinic acid synthetase; biliverdin reductase; heme metabolism

ABSTRACT

2,3,7,8-Tetrachlorodibenzo-*p*-dioxin (TCDD) causes hepatic accumulation of biliverdin and its monoglucuronide in line B rats, but not in line A rats. They are both derived from crosses between TCDD-sensitive Long-Evans (*Turku/AB*; L-E) and TCDD-resistant Han/Wistar (*Kuopio*; H/W) rats. Line A is highly resistant to acute lethality of TCDD due to an H/W-like, altered AHR, while line B is moderately resistant due to H/W-type alleles of an unidentified gene. Since hepatic and splenic heme oxygenase-1 (HO-1), biliverdin IX α reductase (BVRA) and δ -aminolevulinic acid synthetase 1 (ALAS1) are key enzymes in heme metabolism, the effect of TCDD on them was studied at the levels of mRNA (all three enzymes), protein expression (HO-1), and enzymatic activity (BVRA, liver only). In both lines A and B, 300 μ g/kg TCDD transiently repressed hepatic HO-1 mRNA on day 2 but induced HO-1 protein expression at later time-points; however, the impact emerged earlier (day 14 vs. day 35) in line B rats. In spleen, TCDD repressed HO-1 mRNA and protein expression in lines A and B through days 2-35, but did not affect its mRNA levels in L-E rats (10 days after 100 μ g/kg). In all rat strains/lines, there was a strong repression of ALAS1 and a moderate induction of BVRA mRNA in liver, but mostly not in spleen. Hepatic BVRA activity was increased in lines A and B on day 14. At 5 weeks, it was still elevated in line A but only 51% of control in line B. Induced hepatic heme degradation coupled with oxidative stress may underlie biliverdin accumulation in line B.

INTRODUCTION

2,3,7,8-Tetrachlorodibenzo-*p*-dioxin (TCDD) is the most toxic congener among the polychlorinated dibenzo-*p*-dioxins (PCDDs), which are widespread and persistent environmental pollutants. TCDD is known to disturb heme metabolism in at least two ways: it causes porphyria and jaundice (Buu-hoï et al., 1972; Cantoni et al., 1987; Kociba et al., 1976; Pohjanvirta and Tuomisto, 1994). In addition, we have shown in our previous studies (Niittynen et al., 2003, 2007) that TCDD causes hepatic accumulation of the heme degradation product biliverdin and its derivative, biliverdin monoglucuronide, in line B rats. This rat line is moderately TCDD-resistant, and it originates from crosses between highly TCDD-sensitive Long-Evans (*Turku/AB*; L-E; LD50 10-20 µg/kg TCDD) and extremely TCDD-resistant Han/Wistar (*Kuopio*; H/W; LD50 >10,000 µg/kg TCDD) rats (Tuomisto et al., 1999).

The exceptional TCDD resistance of H/W rats is related to a mutated aryl hydrocarbon receptor (AHR) allele (*AHR^{hw}*) and to another, unknown gene *B* allele (*B^{hw}*) (Pohjanvirta, 1990; Tuomisto et al., 1999). The *AHR^{hw}* allele has been shown to harbor a point mutation that results in an abnormal C-terminus transactivation domain and a smaller AHR protein in H/W than in e.g. Sprague-Dawley rats (~98 kDa vs. 106 kDa, respectively) (Elferink and Whitlock, 1994; Pohjanvirta et al., 1998; Pohjanvirta et al., 1999). The identity of gene *B* has not yet been determined, but it may encode a protein participating in the AHR signaling pathway. In order to segregate the two H/W-type TCDD resistance genes into separate rat lines, the H/W and L-E rats were crossbred

(Tuomisto et al., 1999). Two new resultant rat lines were named line A and line B. Line A has the mutated AHR^{hw} allele and the wild-type B allele (genotype $AHR^{hw/hw} B^{wt/wt}$). Line B has the wild-type AHR^{wt} allele but is homozygous for the H/W-type allele of gene B (genotype $AHR^{wt/wt} B^{hw/hw}$). Lines A and B exhibit highly different LD₅₀ values for TCDD: >10,000 µg/kg and 830 µg/kg in males, respectively, and >2,000 µg/kg and 410 µg/kg in females, respectively (Tuomisto et al., 1999). Thus, line A appears to be as resistant as H/W and line B is intermediately resistant.

In the mammalian heme degradation process, heme is cleaved to biliverdin by the rate-limiting enzyme heme oxygenase. The isoform heme oxygenase-1 (HO-1) is often induced in various cellular stress states, such as oxidative stress, and is considered a cytoprotective enzyme (Alam and Cook, 2003). Subsequently, biliverdin is rapidly and quantitatively reduced to bilirubin by biliverdin reductase A (BVRA; McDonagh, 2001) and transferred to liver for conjugation and excretion. For a yet unknown reason, TCDD causes pronounced hepatic accumulation of biliverdin and biliverdin monoglucuronide in line B rats (Niittynen et al., 2003, 2007). The phenomenon is probably related to elevation of serum bilirubin, a well-known effect of TCDD reported in many rat strains/lines, including line B (Buu-Hoï et al., 1972; Kociba et al., 1976; Tuomisto et al., 1999; Zinkl et al., 1973). However, although TCDD induces vast increases in serum bilirubin in L-E rats (Pohjanvirta et al., 1995; Simanainen et al., 2002; Unkila et al., 1994), no definite cases of biliverdin accumulation have been detected in L-E rats after exposure to even lethal doses of TCDD (macroscopic observations in our laboratory, unpublished). Further, the syndrome has never been recorded in rats expressing only the

1
2
3
4 H/W type AHR (genotype *AHR*^{hw/hw}) suggesting that a wild-type AHR with a fully
5
6 functional transactivation domain may be necessary for the biliverdin accumulation
7
8 (Niittynen et al., 2003, 2007). The apparent dependence on genetic factors makes
9
10 biliverdin accumulation an intriguing endpoint of TCDD toxicity from a mechanistic
11
12 point of view.
13
14

15
16
17
18 It was hypothesized that either increased formation of biliverdin due to induction of HO-
19
20 1 or decreased elimination of biliverdin due to decreased activity of BVRA might be the
21
22 immediate reason for its accumulation (Fig. 1). As AHR mediates most effects of TCDD
23
24 through changes in gene expression (Okey, 2007), we first examined the effect of TCDD
25
26 on mRNA expression of HO-1 and BVRA in liver and spleen; the latter organ was
27
28 included as it is the major organ participating in heme degradation. Subsequently, also
29
30 hepatic and splenic HO-1 protein expression and hepatic BVRA activity were analyzed.
31
32 In addition, the effect of TCDD on mRNA expression of the nonspecific form of δ -
33
34 aminolevulinic acid synthetase (ALAS1) was studied. ALAS1 is the first and rate-
35
36 limiting step in heme biosynthesis in nonerythroid cells (May et al., 1995; Fig. 1). TCDD
37
38 and some other cytochrome P450 inducers have been shown to increase its activity
39
40 (Goldstein et al., 1982; Granick, 1966; May et al., 1995; Poland and Glover, 1973). The
41
42 ultimate goal of this study was to look for such changes in gene/protein expression or
43
44 enzymatic activity that might be related to the pathogenesis of hepatic biliverdin
45
46 accumulation. Line B was our main interest, but we also wanted to see whether the
47
48 effects are the same or whether they differ in more TCDD-sensitive or -resistant rats, in
49
50 which the syndrome of biliverdin accumulation has never been observed, and further,
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

whether the AHR genotype has an influence on the outcome. Therefore, L-E and line A rats were examined in addition to line B rats.

MATERIALS AND METHODS

Chemicals

TCDD was purchased from UFA Oil Institute (Ufa, Russia) and was over 98% pure as analyzed by gas chromatography-mass spectrometry. It was dissolved in corn oil. Biliverdin (80% purity) was purchased from Chromatrin, Dublin, Ireland. Tris (99.8%) was obtained from Sigma-Aldrich Chemie, Steinheim, Germany. Sucrose, bovine serum albumin (BSA, minimum 98%) and β -NADPH (97%) were purchased from Sigma-Aldrich Co., St Louis, MO. In BVRA activity measurements, stock solutions of biliverdin and β -NADPH were prepared in 20 mM sodium phosphate buffer ($\text{NaH}_2\text{PO}_4 \cdot \text{H}_2\text{O}$; J.T. Baker, Deventer, Holland), pH 7.2. In HO-1 protein expression analysis, phosphate buffered saline (PBS, pH 7.4) was prepared using dipotassium hydrogen phosphate ($\text{K}_2\text{HPO}_4 \cdot 3\text{H}_2\text{O}$, Merck), $\text{NaH}_2\text{PO}_4 \cdot \text{H}_2\text{O}$ (J.T. Baker) and sodium chloride (NaCl, FF-Chemicals Ab, Yli-Ii, Finland). PBS ingredients were of analytical grade. Nonidet P40 Substitute (NP40) was purchased from Fluka Chemie, Buchs, Switzerland. Hydrochloric acid (HCl, 37 %) and sodium hydroxide (analytical grade) used for adjusting the pH of the solutions were from Merck, Darmstadt, Germany and FF-Chemicals Ab, respectively. In all work involving DNA or RNA, Sigma's water for molecular biology was used. In

all other analysis, purified water (Milli-Q Water purification system, Millipore, Bedford, MA) was used.

Animal husbandry

All rats were obtained from the breeding colony of the National Public Health Institute, Kuopio, Finland. They were housed in groups of 2-4 animals (Experiment I) or singly (Experiment II; see the next section for descriptions of Experiments I and II) in stainless-steel wire-mesh cages with pelleted (Experiment I) or powdered (Experiment II) R36 feed (Lactamin, Stockholm, Sweden) and tap water available *ad libitum*, except for the feed-restricted group in Experiment II. The temperature in the animal room was $21 \pm 1^{\circ}\text{C}$, relative humidity $50 \pm 10\%$ and lighting cycle 12/12 h light/dark. The study plans were approved of by the Animal Experiment Committee of the University of Kuopio and the Kuopio Provincial Government. The procedures were conducted in accordance with the Guidelines of the European Community Council directives 86/609/EEC.

Experimental design

Adult female rats of lines A and B were used in Experiment I. They were 15-20 weeks old at the time of exposure. Rats were randomly divided in groups of 5-7 animals. They were dosed with 300 $\mu\text{g/kg}$ TCDD by gavage (dosing volume 4 ml/kg) and killed 2, 7, 14, 32 or 35 days later by decapitation ($n = 6-7$). Controls received corn oil 4 ml/kg and were decapitated 2 or 35 days later ($n = 5-6$). The dose 300 $\mu\text{g/kg}$ TCDD was chosen because it is large enough to cause the syndrome of hepatic biliverdin accumulation at a fairly high incidence in line B rats (Niittynen et al., 2003). Usually, development of the

1
2
3
4 syndrome takes 3-5 weeks. Thus, we wanted to study possible changes in mRNA/protein
5
6 expression or catalytic activity of selected enzymes of heme metabolism during this time
7
8 period, starting from an early time point (2 days) when no macroscopic changes yet exist,
9
10 and extending the follow-up to day 35 when the syndrome has usually reached its
11
12 maximal severity (characterized by swelling, mottled appearance and dark green or black
13
14 color of the liver, hence the name “black liver syndrome”).
15
16
17
18
19
20

21 In Experiment II, 10- to 13-week-old male L-E rats were used. They received 100 µg/kg
22
23 TCDD by gavage or vehicle (corn oil) and were killed 10 days later by decapitation.
24
25 Since these rats are highly sensitive to TCDD (LD50 ca. 20 µg/kg; Pohjanvirta et al.,
26
27 1993), we had to use a lower dose than that employed in lines A and B. In order to ensure
28
29 that the effects seen were specific to TCDD toxicity and not simply caused by the body
30
31 weight loss accompanying TCDD exposure, Experiment II also included a feed-restricted
32
33 (FR) control group, in which the rats were fed according to a predesigned regimen
34
35 intended to mimic the food intake patterns of L-E rats treated with a lethal dose of
36
37 TCDD. These rats were offered *ad libitum*, 16, 14, 11, 8, 6, 4, 4, 2 and 1 g of powdered
38
39 R36 feed on days 0 through 9, respectively (day 0 denotes the day when the rats were
40
41 dosed). Each experimental group (control, TCDD and FR) consisted of 6 animals.
42
43
44
45
46
47
48
49

50 In both experiments, spleen and a piece of liver were rapidly removed after decapitation
51
52 of the rats, flash-frozen in liquid nitrogen and stored at –80 °C for subsequent analysis. In
53
54 Experiment I, the rest of the liver was used for immediate cytosol preparation (see
55
56
57
58
59
60
61
62
63
64
65

below). When there were prematurely died rats, they were inspected at necropsy, but no samples were collected.

RNA-isolation and RT-PCR

Total RNA was isolated from homogenized liver and spleen samples using GenElute Mammalian Total RNA Miniprep Kit (Sigma-Aldrich, St. Louis, MO). Isolated total RNAs were subjected to DNaseI –treatment with the DNA-free kit (Ambion, Austin, TX). 1.2 µg (or 0.6 µg) of this RNA was then used for reverse transcription in a 20 µl (or 10 µl) reaction that was performed with Omniscript reverse transcriptase (Qiagen, Hilden, Germany) using random hexanucleotides (Roche, Mannheim, Germany) as primers. The reaction mixture was incubated at 37 °C for 1.5 h. Resulting cDNAs were diluted in a 1:6 ratio with water and used in subsequent analysis.

Cloning of ALAS1, HO-1 and BVRA gene fragments

169 to 284-nt-long fragments of ALAS1, HO-1 and BVRA double-stranded cDNAs were cloned using line A rat cDNA as a template. PCR was performed with HotStarTaq DNA polymerase (Qiagen) on TGradient-thermocycler (Biometra, Göttingen, Germany). The “touchdown” method was applied: the annealing temperature was set at 63 °C for the first cycle and then decreased by 1 °C / cycle down to 57 °C. A total of 40 cycles were run. The primers used are shown in Table 1. They were ordered from Sigma-Genosys Ltd., Cambridgeshire, UK. ALAS1, HO-1 and BVRA primers were designed to span at least one intron. In each case, only a single strong amplicon was generated and it was invariably of correct size.

1
2
3
4
5
6
7 PCR products were purified from the agarose gel using Sigma GenElute Gel Extraction
8
9 Kit (Sigma). They were cloned by blunt-end ligation into pCR-Script SK(+) Amp
10
11 plasmids (Stratagene, La Jolla, CA). XLB-1 supercompetent cells were used in
12
13 transformations (Stratagene). The plasmids were purified by Wizard Plus SV Minipreps
14
15 DNA Purification System (Promega, Madison, WI). The inserts were sequenced with an
16
17 A.L.F.express DNA sequencer (Amersham-Pharmacia Biotech, Uppsala, Sweden)
18
19 using Thermo Sequenase CY5 Dye Terminator Kit (Amersham-Pharmacia Biotech).
20
21 Previously prepared CYP1A1, CYP1A2 and β -actin plasmids as well as a purified PCR
22
23 product of GAPDH (Korkalainen et al., 2004; Korkalainen et al., 2005, Pohjanvirta et al.,
24
25 2006; Table 1) were also used for production of external standard curves in mRNA
26
27 quantitation.
28
29
30
31
32
33
34
35

36 **Real-time quantitative PCR**

37
38 The mRNA expression levels of ALAS1, HO-1, BVRA, CYP1A1, CYP1A2, GAPDH
39
40 and β -actin were analyzed using QuantiTect SYBR Green PCR Kit (Qiagen) and Rotor-
41
42 Gene 2000 Real-Time Amplification System (Corbett Research, Mortlake, NSW,
43
44 Australia). The 20 μ l reaction mixture contained cDNA derived from 15 ng of total RNA,
45
46 0.5 μ M each primer and 10 μ l QuantiTect. The PCR was initiated with an incubation step
47
48 of 15 min at 95 °C to activate HotStarTaq DNA polymerase. The “touchdown” method
49
50 was applied: the annealing temperature was set at 63 °C for the first cycle and then
51
52 decreased by 1 °C / cycle down to 57 °C. The cycling procedure was denaturation at 95
53
54 °C for 20 s, annealing at 57 °C for 20 s, and extension at 72 °C for 20 s with fluorescence
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4 acquired. A total of 45 cycles were run. A melting curve was run at 55-99 °C to verify the
5
6 specificity of PCR products. Standard curves were generated to determine the absolute
7
8 amount of template in each reaction. To this end, plasmid DNAs were linearized and
9
10 quantified by spectrophotometry. Standard curve PCRs were carried out using 1-4
11
12 replicates of each dilution of plasmid. The used dilutions varied between 10^{-4} - 10^{-11}
13
14 (relative to original plasmid at a concentration of 200 ng/μl). The Rotor-Gene 2000
15
16 version 4.6 software was employed to obtain the threshold cycle (C_t) for best fit (least
17
18 squares method) of the standard curve. The C_t values were then converted to
19
20 concentrations by the formula:
21
22
23
24

$$\text{Calculated concentration} = 10^{(\text{slope} \times C_t + \text{intercept})}$$

25
26
27
28 The instrument analysis software was always allowed to carry out dynamic tube
29
30 corrections. Reaction efficiencies were between 85 and 99%. All R values were > 0.996 .
31
32
33 A negative control containing all the components of the reaction mixture but water
34
35 replacing the template was included in each run. Line B liver samples were analyzed in
36
37 duplicate in two separate runs: one run consisting of the groups control (day 2), TCDD
38
39 (day 2) and TCDD (day 7), and the other of the groups control (day 35), TCDD (day 14)
40
41 and TCDD (day 32). Because the results of duplicates showed good reproducibility, the
42
43 rest of the samples were analyzed only as single measurements as this enabled us to run
44
45 all the samples of a single tissue from a given strain/line at the same time.
46
47
48
49
50
51
52

53 **Concentration of the HO-1 protein**

54
55 Hepatic and splenic concentration of HO-1 protein was determined in selected samples
56
57 using the Rat Heme Oxygenase-1 EIA Kit (Precoated; Takara Bio Inc., Otsu Shiga,
58
59
60
61
62
63
64
65

Japan). The kit is a solid phase EIA Kit based on a sandwich method utilizing two mouse monoclonal anti-rat heme oxygenase-1 antibodies to detect rat heme oxygenase-1 by a two-step procedure. The assay was carried out on a precoated 96-well plate. A piece (about 50-90 mg) of deep-frozen liver or spleen was weighed and homogenized in extraction buffer (1 % NP40 in PBS) for 30 s using Ultra Turrax -homogenizer (T25 basic, IKA Labortechnik). The homogenates were centrifuged (21,000 x g, 10 min, 4 °C), after which the supernatants were collected and stored at -80 °C until analysis. 1:20 (liver) and 1:2000 (spleen) dilutions of supernatants, prepared in the kit's sample diluent, were used for analysis of HO-1 concentration. The analysis was carried out according to the manufacture's instructions. Standard series consisted of 0.125, 0.25, 0.5, 1, 2, 4 and 8 ng/ml dilutions of HO-1 protein. Both the samples and the standards were analyzed in duplicates. After the completion of the assay, the plate was read at 450 nm using a microplate reader (Labsystems IEMS Reader MF, Labsystems Oy, Helsinki, Finland). As the most dilute standards (0.125-0.5 ng/ml) did not reproducibly differ from the blank (kit's sample diluent), they were ignored. The *R*-values of the standard series were 0.994 and 0.992 for liver and spleen analyses, respectively. Nearly all values for the samples were encompassed by the standard series, except for a few liver samples, which exceeded the highest standard. They were re-analyzed as 1:160 dilutions, and at that time, values for the samples were encompassed by the standard series (*R* = 0.991). Total protein concentrations of the supernatants were analyzed as explained below. The concentration of HO-1 protein in supernatants was normalized to total protein concentration, and the result was expressed as the amount of HO-1 protein in ng per mg total protein.

BVRA activity

BVRA activity was determined in liver cytosols of line A and line B rats. Livers were perfused *in situ* for 4 min with 0.9 % NaCl (Natrosteril, Orion, Finland) right after decapitation of the rat. The first ca. 30 s of perfusion was done using room-temperated NaCl followed by cold NaCl for the rest of the time. Perfusion was made through portal vein – inferior vena cava. A piece of liver (~ 2-4 g) was homogenized in 4 volumes of filter-sterilized ice-cold buffer (10 mM Tris and 0.25 M sucrose, pH 7.5 with HCl) using Teflon-pestled Potter-Elvehjelm glass homogenizer in a Heidolph homogenizer device. Homogenates were centrifuged for 20 min at 11,100 x g, at 4 °C. The supernatant was transferred into an ultracentrifuge tube and centrifuged for 1 hr at 100,000 x g, 4 °C. The resulting cytosols were flash-frozen in liquid nitrogen and stored at -80 °C.

BVRA activity was measured at room temperature (23 °C) using Shimadzu UV-1601 spectrophotometer (Fennolab, Fenno Medical Oy, Kyoto, Japan) and Starna Brand 1 cm cuvetts (Optiglass Ltd, Hainault, Essex, UK). BVRA activity was identified as a spontaneous increase in absorbance at wavelength 460 nm, reflecting the formation of bilirubin in the solution. The initial composition of the reaction (volume = 3.08 ml) was 100 mM Tris (pH 8), 10 µM biliverdin, and 150 µl of cytosol. Immediately after mixing these components, the reaction was followed for 10 x 1 minutes to record the blank rate. After this, β-NADPH was added to the solution to a concentration of 100 µM and the reaction was followed again for 10 x 1 min to record the BVRA-activity. Total volume of the reaction was 3.1 ml. Total protein concentrations of the cytosols were analyzed as explained below.

1
2
3
4
5
6
7 The mean of recordings between 6 and 10 minutes was used as the value for blank rate
8
9 and the mean of recordings between 7 and 10 minutes after addition of β -NADPH as the
10
11 value for BVRA-activity (dA/min). The amount of bilirubin formed in a minute was
12
13 calculated using the molar absorption coefficient of $52,500 \text{ l mol}^{-1} \text{ cm}^{-1}$ (Rigney et al.,
14
15 1989). This was then divided by the total protein concentration of the cytosol to get the
16
17 BVRA activity expressed as the amount of bilirubin formed (nmol/min/mg total protein).
18
19
20
21
22

23 24 **Total protein concentration**

25
26 Total protein concentrations were analyzed using Bio-Rad Protein Assay Dye Reagent
27
28 Concentrate (Bio-Rad Laboratories, Hercules, CA). 1:50 dilutions of the cytosoles
29
30 (BVRA activity assessment) and 1:40 and 1:20 dilutions of hepatic and splenic
31
32 supernatants (HO-1 protein concentration assessment), respectively, were prepared for
33
34 the analysis. Dilutions of BSA at concentrations of 0.03125, 0.0625, 0.125, 0.25 and 0.5
35
36 mg/ml were used as standards. Assays were made on 96-well plates. 20 μl of water
37
38 (blank), standard or diluted sample was applied in the wells and 200 μl of the Protein
39
40 Assay Dye Reagent was added on top. The plate was gently mixed for 5 min, and the
41
42 absorbances of the wells were recorded with a microplate reader at wavelength 595 nm
43
44 (Labsystems iEMS Reader MF, Labsystems Oy, Helsinki, Finland). The samples and
45
46 standards were measured in triplicates. The Labsystems Genesis V2.12 software was
47
48 employed to create standard curves. All regression coefficients were > 0.991 . The signals
49
50 of the samples were converted to protein concentrations by the formula: concentration =
51
52 (absorbance – intercept)/slope.
53
54
55
56
57
58
59
60
61
62
63
64
65

Statistical analysis

Groups of each strain/line were compared using the one-way analysis of variance (ANOVA). If this test showed a significant difference, the least significant difference test was used as a *post-hoc* test. In case of non-homogenous variances (according to Levene's test, $p < 0.05$), the non-parametric Kruskal-Wallis ANOVA was used and followed by the Mann-Whitney U test. P -values less than 0.05 were considered statistically significant. In Experiment I, the controls were from two time points, 2 and 35 days after vehicle administration (referred to as C2 and C35 control groups, respectively). Using Student's t -test, or in case of nonhomogenous variances, Mann-Whitney U test, we verified that for most variables analyzed, there was no significant difference between these two control groups ($p > 0.05$). Therefore, they were pooled to form one control group ($n = 10-12$). In a few cases, however, C2 and C35 groups differed significantly from each other ($p < 0.05$) and were thus kept separate.

In the real-time quantitative RT-PCR analysis, some samples had HO-1 mRNA content less than the detection limit (line A: 3, 2 and 2 samples from days 2, 7 and 14, respectively; L-E-strain: two samples in FR group). These samples were given the lowest detectable value of the variable under study.

RESULTS

Macroscopic observations

As expected, the used doses of TCDD resulted in significant impacts on body weight in both line B and L-E rats, but only a mild effect was observed in TCDD-resistant line A rats (Table 2). Line B rats were exposed to a dose of TCDD close to their LD50 value. All rats in Experiment I survived for two weeks, but thereafter five out of seven line B rats succumbed prematurely and no samples were obtained from them, but they were examined at necropsy and macroscopic changes recorded. The remaining two rats of the group were sampled three days earlier than intended (day 32 instead of 35).

There were changes in liver appearance in line A and B rats at the latest time point (Table 2). In line B, the incidence of 57 % (4/7) of livers with accumulation of dark green/black pigment is in good agreement with our previous results (Niittynen et al., 2003). Thirty-five days after TCDD exposure, 5 out of 6 line A rats had a yellowish liver, which might result from accumulation of bilirubin in the liver. Increased serum bilirubin levels have been reported in resistant rat strains (line A and H/W rats), although they are far lower than those in more sensitive strains (Unkila et al., 1994; Tuomisto et al., 1999).

mRNA expression levels

By and large, the effects of TCDD on the mRNA expression levels analyzed were similar in line A and line B rats (Figs. 2 and 3), in both liver and spleen. Also Experiment II on L-E rats yielded concordant results (Fig. 4), except for splenic HO-1.

Selection of a housekeeping gene for normalization of the mRNA expression data

Initially, we intended to use β -actin for normalization of the mRNA expression data. However, its hepatic expression increased due to TCDD in L-E and line B rats when exposure lasted 7 days or more (Pohjanvirta et al., 2006). In line A, the increase was seen only at the latest time-point (day 35). In the study of Pohjanvirta et al. (2006), 18 commonly applied housekeeping genes were studied in order to find a widely-applicable housekeeping gene for acute toxicity studies of TCDD. *GAPDH* was one the most stable genes and therefore, was used here for normalization of the gene expression data derived from liver. β -Actin mRNA was used for normalization of gene expression data derived from spleen, as it was stable in that organ.

CYP1A1 and CYP1A2

CYP1A1 and CYP1A2 mRNAs, which were used as positive controls of induction, showed the characteristic elevation in liver after TCDD exposure (Figs. 2 and 4). Maximal CYP1A1 induction was about 4650-fold (line B, day 7), whereas maximal CYP1A2 induction was 18 to 26-fold (line B, day 7; relative to C35- and C2-groups, respectively). Thus, there is a large quantitative difference in the induction of these two enzymes by TCDD. In addition, it seems that CYP1A1 induction may be more pronounced in line B than in line A (means \pm S.D. of maximal fold inductions 4652 ± 891 and 2788 ± 619 , respectively).

ALAS1, HO-1 and BVRA

TCDD significantly decreased hepatic expression of ALAS1 mRNA (Figs. 2 and 4). In line B, ALAS1 mRNA expression was 37% of control value already on day 2, and fell further down to 14% by day 14. The effect was similar in lines A and B and also in L-E rats, so it is not dependent on AHR genotype or TCDD sensitivity, and thus can be classified as type I dioxin effect, where the effect is independent of the AHR genotype (for definition of type I and type II effects, see Simanainen et al., 2002). In feed-restricted L-E rats, ALAS1 mRNA expression increased, implying that the repression is caused by TCDD and not secondary to body weight loss. TCDD did not influence splenic ALAS1 mRNA expression in any rat strain/line.

HO-1 mRNA was not induced by TCDD in liver (Figs. 2 and 4). Rather, in both lines A and B, hepatic *HO-1* expression showed a downward tendency on day 2 with mean mRNA levels being 17% ($p < 0.05$) and 22% ($p < 0.05$, compared with the C2 group) of control, respectively. In spleen, HO-1 mRNA expression was decreased after TCDD exposure in both rat lines A and B throughout the observation period (Fig. 3). In contrast, no significant departure from control value was seen in L-E rats (Fig. 4). In fact, there was a slight upward tendency in the TCDD-exposed group.

Interestingly, there seemed to be a rather large difference in the basal expression level of HO-1 mRNA between line A and line B rats (Fig. 2; control groups). Technical matters may at least partly account for this, since line A and line B samples were analyzed in

different real-time quantitative PCR runs and also cDNAs were prepared separately. However, we wanted to clarify whether there indeed are differences in the basal expression level of HO-1 mRNA between the rat strains/lines. To this end, new cDNAs were prepared from liver samples of line A, line B and L-E control rats. Subsequently, HO-1 and β -actin mRNA levels were analyzed (here it was possible to use β -actin for normalization, since no TCDD was involved). In this analysis, all samples from different strains/lines were prepared and analyzed at the same time in order to minimize confounding factors. It was found out that in line B ($n = 10$) and L-E ($n = 6$) control rats the expression level of HO-1 mRNA was 2.5-fold ($p < 0.001$) and 1.7-fold ($p < 0.05$), respectively, higher relative to line A ($n = 10$). This implies that there indeed may be differences in the basal expression level of *HO-1* among rat strains/lines.

Hepatic expression of BVRA mRNA increased somewhat in all rat strains/lines after TCDD exposure. In line A, the effect was seen on days 14 and 35 (2.4- and 3.3-fold increase, respectively; Fig. 2). In line B, a slight increase (1.75-fold) was seen on day 7 (Fig. 2). BVRA mRNA expression increased also in L-E rats after TCDD-exposure (2.2-fold on day 10; Fig. 4), but was unchanged in feed-restricted rats. This implies that the effect is related to TCDD exposure and not simply due to body weight loss. In spleen, BVRA mRNA expression did not significantly change due to TCDD exposure in lines A or B (Fig. 3) but increased 1.7-fold in L-E rats on day 10 (Fig. 4).

Expression of HO-1 protein

For technical reasons, expression of HO-1 protein was analyzed only in selected samples. The later time-points (14 and 32-35 days) were regarded as most appropriate, since the accumulation of biliverdin is macroscopically seen at the earliest about 3 weeks after TCDD exposure. Samples from day 2 were also analyzed (line B only), since there was a repression of HO-1 mRNA on that day (Fig. 2).

In line A, TCDD had no influence on expression of HO-1 protein on day 14, but induced its expression clearly on day 35 (Fig. 5). The mean induction was 6.5-fold, however, individual differences were remarkable with the maximum individual induction being 14.5-fold. In line B, expression levels of HO-1 differed in C2 and C35 control groups, the concentration in the latter being only 58 % of that in the former (Fig. 5). Therefore the exposed groups were compared separately with C2 and C35. A significant decrease in HO-1 expression (45 % of the C2) was found on day 2. This is in accordance with HO-1 mRNA expression (Fig. 2). At later time points, HO-1 protein expression was induced: on day 14 it was 2.8- ($p = 0.114$) and 4.8-fold ($p = 0.016$) relative to C2 and C35, respectively. Similarly to line A, individual differences were very large. On day 32, the mean value of HO-1 protein concentration was 2.4- and 4.1-fold higher relative to C2 and C35, respectively, but the induction was not statistically significant due to the small number of rats in the TCDD group. In contrast to HO-1 mRNA levels, there was no significant difference ($p = 0.094$) between the hepatic concentrations of HO-1 protein in line A and line B rats on post-vehicle day 35 (day 2 could not be analyzed for this aspect as HO-1 protein concentration was not assessed in line A samples from day 2).

1
2
3
4
5
6
7 The Pearson correlations between hepatic HO-1 mRNA and HO-1 protein were 0.608 (p
8 = 0.036) and 0.558 ($p = 0.013$) in line A and line B, respectively, indicating a moderate-
9 to-good correlation. In spleen, HO-1 protein concentration decreased by ca. 20 % in both
10 lines A and B after TCDD exposure, although in line B only relative to C35 (Fig. 5). The
11 Pearson correlations between splenic HO-1 mRNA and protein concentrations were
12 0.745 ($p = 0.008$) and 0.657 ($p = 0.003$) in lines A and B, respectively, indicating even
13 stronger concordances than in liver.
14
15
16
17
18
19
20
21
22
23
24
25

26 **Enzymatic activity of BVRA**

27
28 TCDD increased the catalytic activity of liver cytosolic BVRA in both rat lines (Fig. 6).
29
30 In line A, 1.3-, 1.5- and 1.5-fold increases were observed at days 2, 14 and 35,
31 respectively. In line B a 1.5-fold increase was seen on day 14. However, this increase in
32 line B rats flipped to 50% reduction by day 32.
33
34
35
36
37
38
39
40

41 Interestingly, in line A, TCDD had a significant effect on the blank rate (the rate detected
42 in a reaction mix containing buffer, biliverdin and cytosol, but not NADPH), increasing it
43 more than 2-fold at 2, 7 and 14 days (Fig. 6). A similar but milder effect was seen in line
44 B rats at 2 days. Blank rate should represent the unspecific (non-enzymatic) change in
45 absorbance at 460 nm. However, an enzymatic reaction is also possible with endogenous
46 NADPH (and possibly NADH) in the cytosol. TCDD has been shown to initially increase
47 hepatic NADPH content (Stohs et al., 1990), which might explain the increase in the
48 blank rate after TCDD exposure. At the last time point, the blank rate was again at the
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

control level in line A but only 9 % of the control in line B. The latter observation might reflect depletion of NADPH during the possible TCDD-induced severe oxidative stress (Stohs, 1990) or through inappropriately active *de novo* synthesis of fatty acids and/or cholesterol.

DISCUSSION

Hepatic accumulation of biliverdin is a novel TCDD-induced phenomenon reported only in some intermediately TCDD-resistant rats, predominantly those of line B, developed in our laboratory (Niittynen et al., 2003). In the present study, the effect of TCDD on the enzymes responsible for the formation and elimination of biliverdin was studied in order to look for possible TCDD-induced derailments in their activity or expression that might play a role in biliverdin accumulation.

HO-1

Two days after TCDD exposure (300 µg/kg), mRNA expression of HO-1 was repressed in liver and spleen; in the latter organ this repression remained throughout the whole observation period of 35 days. In liver, HO-1 mRNA concentration returned to the control level at later time-points. In accordance with the changes in HO-1 mRNA, also HO-1 protein expression was decreased on day 2 (analyzed in line B). However, HO-1 protein was clearly induced 14 and 32 days after TCDD exposure in line B, and on day 35 in line A. HO-1 is regarded to be regulated mainly at the transcriptional level (Alam

1
2
3
4 and Cook, 2003; Morse and Choi, 2002), and findings from our correlation analyses of
5
6 HO-1 mRNA and protein expression are in good agreement with this view in both liver
7
8 and spleen. However, since the mean induction of HO-1 protein is manifold compared
9
10 with the mean increase in mRNA levels, our results suggest that post-transcriptional
11
12 mechanisms are also involved in regulation of HO-1 expression in rat liver. This seems to
13
14 hold also in spleen, since a large reduction in HO-1 mRNA levels resulted in a much
15
16 smaller reduction in HO-1 protein concentrations (compared as percentages).
17
18
19
20
21
22

23
24 Induction of HO-1 protein expression 14-32 or 35 days after TCDD exposure in line B
25
26 and line A rats, respectively, suggests that degradation of heme may be increased in rat
27
28 liver due to TCDD exposure. On the other hand, the initial (day 2) repression of HO-1 at
29
30 both mRNA and protein levels suggests that HO-1 induction is not a direct effect of
31
32 TCDD on *HO-1* gene. More likely, induction of HO-1 might be caused by some TCDD-
33
34 triggered change in cellular homeostasis. This kind of change might be increased
35
36 production of reactive oxygen species (ROS), a known consequence of TCDD exposure
37
38 (Senft et al., 2002; Stohs, 1990) and an established inducer of HO-1 (Ryter and Choi,
39
40 2002). In addition, the substrate heme is a well-known inducer and feed-back regulator of
41
42 HO-1 (Shibahara, 2003). Therefore, if TCDD increased hepatic free heme level, this
43
44 might lead to HO-1 induction. However, no studies of TCDD's effect on hepatic free
45
46 heme concentrations could be found in the literature. Furthermore, both ROS and heme
47
48 are known to mediate HO-1 induction at the transcriptional level, but here it seems that
49
50 the main regulation would occur post-transcriptionally. Importantly, hepatic induction of
51
52 HO-1 protein was seen in both line A and line B rats, although it emerged earlier in line
53
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4 B. This indicates that TCDD can induce hepatic expression of HO-1 protein both in rats
5
6 with mutated, H/W-type AHR and in rats with wild-type AHR. However, altered AHR
7
8 may delay the onset of induction.
9

10
11
12
13
14 Another rat strain-associated difference in hepatic HO-1 was the difference in basal level
15
16 of HO-1 mRNA especially between line A and line B rats. However, there was no
17
18 significant difference in HO-1 protein levels between line A and line B control rats on
19
20 post-vehicle day 35. Thus, the observed difference in mRNA level may be of minor
21
22 importance as to action of HO-1 enzyme and its effects in liver. However, also this
23
24 observation suggests that AHR genotype may have some influence on the regulation of
25
26 *HO-1* expression.
27
28
29

30
31
32
33 Only hypothetical reasons for repression of splenic HO-1 expression can be given. Two
34
35 such phenomena are hypoxia and feed-back regulation by intracellular heme. Repression
36
37 of HO-1 has been demonstrated in cultured human cells due to hypoxia with the
38
39 potentially beneficial consequences such as reduction of energy expenditure and
40
41 prevention of local accumulation of CO, iron and bilirubin (Shibahara, 2003). On the
42
43 other hand, it has been suggested that HO-1 is normally induced in spleen due to large
44
45 amounts of heme present (Braggins et al., 1986). Therefore, if the amount of heme in
46
47 spleen reduced then the concentrations of HO-1 protein and mRNA might decrease.
48
49 Overall, the consequences of TCDD exposure on HO-1 expression seem to be largely
50
51 different in spleen and in liver. This is not surprising, since HO-1 is often regulated in a
52
53 tissue-specific manner (Shibahara, 2003). Splenic repression of HO-1 was not observed
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4 in L-E rats. Gender, TCDD-dose, TCDD-sensitivity, duration of exposure as well as
5
6 *AHR*- and gene *B* -genotypes are factors that may underlie the difference between L-E
7
8 versus line A and B rats.
9

10 11 12 13 14 **BVRA**

15
16 Hepatic BVRA activity was increased (1.5-fold) in both line A and line B rats 14 days
17
18 after TCDD exposure suggesting enhanced capacity of hepatic biliverdin reduction.
19
20 Induction seems to occur at the transcriptional level since also hepatic BVRA mRNA
21
22 levels were elevated in all three rat strains after TCDD exposure. The next question is,
23
24 why and how does TCDD induce BVRA? There are only few previous reports where
25
26 induction of BVRA has been described in any conditions. McCoubrey et al. (1995)
27
28 reported about 2-fold induction of BVRA mRNA after hyperthermia in rat kidney and
29
30 Maines et al. (1999) observed a 175 % increase in transcript level in human renal
31
32 carcinoma. Interestingly, the induction levels reported in the above-mentioned studies are
33
34 similar to our observations although the causative agent is different. A possible molecular
35
36 route for increased BVRA mRNA could be induction of AP-1 transcription factors by
37
38 TCDD (Puga et al., 2000), as BVRA gene has an AP-1 binding site in its promoter
39
40 (McCoubrey et al., 1995).
41
42
43
44
45
46
47
48
49

50
51 Similarly to induction of HO-1, also induction of BVRA takes place predominantly only
52
53 after a delay (2 weeks) from TCDD exposure. In line A, induction of BVRA preceded
54
55 that of HO-1, as the former occurred on day 14, when the amount of HO-1 protein was
56
57 still at the control level.
58
59
60
61
62
63
64
65

Potentially interesting is the difference in the BVRA activity between line A and line B rats on day 32/35. At that time-point, line B rats had severe accumulation of biliverdin (enlarged liver containing dark green/black pigment) and the activity of BVRA was diminished down to 51 % of control. In contrast, line A rats exhibited increased activity of BVRA on day 35 and their livers were yellowish. It is possible that decreased BVRA activity in line B rats is due to the overt liver damage at that stage. On the other hand, the possibility remains that between days 14 and 32, BVRA activity would start to diminish in line B rats, and this would lead to biliverdin accumulation. Even so, the late reduction in BVRA activity could hardly be the only or primary reason for the syndrome, since it was preceded by induction of BVRA on day 14. A more likely scenario is that accumulation of biliverdin is preceded by increased bilirubin concentration (as bilirubin glucuronides) in hepatocytes due to its diminished clearance (Choe and Yang, 1983; Peterson et al. 1979; Yang et al., 1983) and/or augmented formation (Mitchell et al., 1990), and oxidized back in line B to biliverdin glucuronides due to severe and prolonged oxidative stress caused by TCDD. This is supported by the fact that biliverdin glucuronides, not free biliverdin, seem to constitute the bulk of the pigment (Niittynen et al.; unpublished results). With biliverdin starting to accumulate, BVRA could be partly inactivated due to substrate inhibition, i.e. formation of an enzyme-NADP-biliverdin complex (Rigney and Mantle, 1988).

Better knowledge of the mechanism of increased serum bilirubin levels, a well-known effect of TCDD, might further help ascertain the reason for biliverdin accumulation.

Unfortunately, no conclusive evidence exists in the literature as to whether the increase in serum bilirubin after TCDD exposure is due to its decreased secretion or increased formation or both (see e.g. Pohjanvirta and Tuomisto, 1994 and references therein). One possible reason is hepatobiliary dysfunction (Peterson et al., 1979) resulting in cholestasis or decreased secretion of bilirubin to bile. However, we recently found that bile bilirubin levels were increased about 2.6-fold relative to control in TCDD-sensitive rats 7 days after 10 µg/kg TCDD (unpublished data). This does not support the view that decreased secretion of bilirubin from hepatocytes to bile would be the key (or at least the sole) reason for increased serum bilirubin levels. Other possibilities are that the (re)uptake of bilirubin at the sinusoidal membrane of hepatocytes is impaired by TCDD or that its hepatic synthesis is enhanced. The latter option is supported by the current results showing induction of HO-1 and BVRA after TCDD exposure. At least part of the increase in bilirubin levels could conceivably be due to its increased *de novo* formation since the hepatic enzymes responsible for its formation are induced. However, while BVRA seems to be as efficiently induced in line A as in line B, bilirubin is much less increased in line A serum than in line B serum after TCDD exposure (Tuomisto et al., 1999). Moreover, BVRA is not a rate-limiting enzyme (Fig. 1). Thus, TCDD may cause problems in bilirubin clearance especially in line B and other rat strains/lines with wild-type AHR. Another possibility is that there might be less substrate (biliverdin) for BVRA available in line A than in line B rats, but the HO-1 data do not support this. Future studies are still needed to fill the gap in our current understanding of the basis for increased serum bilirubin levels after TCDD exposure.

1
2
3
4 Interestingly, in line A, TCDD increased the blank rate in BVRA activity measurements
5
6 on days 2, 7 and 14. This is possibly due to an increased amount of endogenous NADPH,
7
8 the limiting factor of the reaction, as it has been shown that 100 µg/kg of TCDD
9
10 increased NADPH content in the livers of Sprague-Dawley rats until day 5, whereafter its
11
12 amount was reduced below the control level (Stohs et al., 1990). However, in line B, only
13
14 a slight increase in blank rate was observed and only on day 2. Furthermore, line B
15
16 control rats had a somewhat higher blank rate than line A control rats. The presumed
17
18 increase in cytosolic NADPH content in line A rats might be a protection mechanism,
19
20 while the drastic reduction in blank rate in line B rats on day 32 might be an indicator of
21
22 severe oxidative stress, if it is indeed due to a reduced NADPH content in the liver (Stohs
23
24 et al., 1990). Altogether these observations suggest differences in the degree of TCDD-
25
26 induced oxidative stress between line A and line B and/or in the ability of these rat lines
27
28 to handle the oxidative insult resulting from TCDD treatment.
29
30
31
32
33
34
35
36
37

38 **ALAS1**

39
40 Repression of hepatic ALAS1 mRNA expression after TCDD exposure was a consistent
41
42 finding in all three rat strains. Repression was specific to liver, as the expression did not
43
44 change in spleen. A possible reason for ALAS1 repression is increased amount of free
45
46 heme, which is a well-known feed-back repressor of ALAS1 gene expression in liver
47
48 (Yamamoto et al., 1988). Heme negatively regulates ALAS1 expression by decreasing
49
50 mRNA half-life (Hamilton et al., 1991) and may also inhibit ALAS1 gene transcription
51
52 (Srivastava et al., 1988). Thus, two observations of this study, induction of HO-1 and
53
54 repression of ALAS1, are conditions which can be caused by free heme. This warrants
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4 future studies on TCDD's interference with hepatic free heme content. The pattern of
5
6 ALAS-1 repression and HO-1 induction has been observed in acute liver failure in
7
8 humans (Fujii et al., 2004) and in the rat model of septic multiple organ dysfunction
9
10 syndrome (Suzuki et al., 2000). In these cases, it was proposed that the causative agent
11
12 was increased free heme concentration. In addition to the elevated free heme level,
13
14 another possible cause for ALAS1 repression has been proposed. Guberman et al. (2003)
15
16 suggested that activator protein-1 (AP-1) complex has an inhibitory effect on ALAS1
17
18 expression, and TCDD has been shown to induce AP-1 (Puga et al., 2000). It is also
19
20 noteworthy that the repression of ALAS1 found here after a single exposure to relatively
21
22 high, even lethal dose (depending on the rat strain) of TCDD is at variance with its
23
24 induction reported after repeated exposure of Sprague-Dawley rats to a low dose (1
25
26 $\mu\text{g/kg/week}$) of TCDD for 16 weeks (Goldstein et al., 1982).
27
28
29
30
31
32
33
34
35

36 In conclusion, the results suggest that hepatic heme degradation is induced by TCDD in
37
38 the rat strains/lines studied. However, this does not alone explain the biliverdin
39
40 accumulation in line B rats. The repression of BVRA activity may be an important
41
42 contributor, but probably there are also problems in bilirubin secretion and/or severe
43
44 oxidative stress, which might lead to the oxidation of bilirubin and its glucuronides to
45
46 biliverdin and respective glucuronides.
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

ACKNOWLEDGEMENTS

We thank Dr. Merja Korkalainen for assistance in preparing the HO-1 plasmid and Ms. Arja Tamminen and Ms. Virpi Tiihonen for assistance in animal experiments. We also wish to thank Dr. Tim Mantle for an opportunity to M.N. to visit his laboratory in Trinity College, Dublin, and Dr. Edward Franklin for excellent guidance in BVRA activity measurements. Prof. emeritus Jouko Tuomisto is acknowledged for helpful discussions throughout the experiments and for critical reading of the manuscript. This study was financially supported by the Academy of Finland (grants 53307, 211120 and 123345), the Emil Aaltonen Foundation, the Finnish Cultural Foundation and the Graduate School in Environmental Health SYTYKE.

CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest.

REFERENCES

- Alam, J., Cook, J. L., 2003. Transcriptional regulation of the heme oxygenase-1 gene via the stress response element pathway. *Curr. Pharm. Des.* 9, 2499-2511.
- Braggins, P. E., Trakshel, G. M., Kutty, R. K., Maines, M. D., 1986. Characterization of two heme oxygenase isoforms in rat spleen: comparison with the hematin-induced and constitutive isoforms of the liver. *Biochem. Biophys. Res. Commun.* 141, 528-533.
- Buu-Hoï, N. P., Chanh, P. H., Sesqué, G., Azum-Gelade, M. C., Saint-Ruf, G., 1972. Enzymatic functions as targets of the toxicity of "Dioxin" (2,3,7,8-tetrachlorodibenzo-*p*-dioxin). *Naturwissenschaften* 59, 173-174.
- Cantoni, L., Rizzardini, M., Graziani, A., Carugo, C., Garattini, S., 1987. Effects of chlorinated organics on intermediates in the heme pathway and on uroporphyrinogen decarboxylase. *Ann. N.Y. Acad. Sci.* 514, 128-140.
- Choe, S.Y., Yang K.H., 1983. Effect of butylated hydroxytoluene (BHT) and butylated hydroxyanisole (BHA) on carbon tetrachloride and TCDD hepatotoxicity. *Korean Biochem. J.* 16, 315-321.
- Elferink, C. J., Whitlock, J.P., 1994. Dioxin-dependent, DNA sequence-specific binding of a multiprotein complex containing the Ah receptor. *Receptor* 4, 157-173.
- Goldstein J. A., Linko P., Bergman H., 1982. Induction of porphyria in the rat by chronic versus acute exposure to 2,3,7,8-tetrachlorodibenzo-*p*-dioxin. *Biochem. Pharmacol.* 31, 1607-1613.

Granick, S., 1966. The induction *in vitro* of the synthesis of δ -aminolevulinic acid synthetase in chemical porphyria: a response to certain drugs, sex hormones, and foreign chemicals. J. Biol. Chem. 241, 1359-1375.

Guberman, A. S., Scassa, M. E., Giono, L. E., Varone, C. L., Canepa, E. T., 2003. Inhibitory effect of AP-1 complex on 5-aminolevulinate synthase gene expression through sequestration of cAMP-response element protein (CRE)-binding protein (CBP) coactivator. J. Biol. Chem. 278, 2317-2326.

Hamilton, J. W., Bement, W. J., Sinclair, P. R., Sinclair, J. F., Alcedo, J. A., Wetterhahn, K. E., 1991. Heme regulates hepatic 5-aminolevulinate synthase mRNA expression by decreasing mRNA half-life and not by altering its rate of transcription. Arch. Biochem. Biophys. 289, 387-392.

Fujii H., Takahashi T., Matsumi M., Kaku R., Shimizu H., Yokoyama M., Ohmori E., Yagi T., Sadamori H., Tanaka N., Akagi R., Morita K., 2004. Increased heme oxygenase-1 and decreased δ -aminolevulinate synthase expression in the liver of patients with acute liver failure. Int. J. Mol. Med. 14, 1001-1005.

Kociba, R. J., Keeler, P. A., Park, C. N., Gehring, P. J., 1976. 2,3,7,8-Tetrachlorodibenzo-*p*-dioxin (TCDD): results of a 13-week oral toxicity study in rats. Toxicol. Appl. Pharmacol. 35, 553-574.

Korkalainen, M., Tuomisto, J., Pohjanvirta, R., 2004. Primary structure and inducibility by 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD) of aryl hydrocarbon receptor repressor in

1
2
3
4 a TCDD-sensitive and a TCDD-resistant rat strain. *Biochem. Biophys. Res. Commun.*
5
6 315, 123-131.
7
8

9
10 Korkalainen, M., Lindén, J., Tuomisto, J., Pohjanvirta, R., 2005. Effect of TCDD on
11
12 mRNA expression of genes encoding bHLH/PAS proteins in rat hypothalamus.
13
14 *Toxicology* 208, 1-11.
15
16

17
18 Maines, M. D., Mayer, R. D., Erturk, E., Huang, T. J., Disantagnese, A., 1999. The
19
20 oxidoreductase, biliverdin reductase, is induced in human renal carcinoma - pH and
21
22 cofactor-specific increase in activity. *J. Urol.* 162, 1467-1472.
23
24

25
26 May, B. K., Dogra, S. C., Sadlon, T. J., Bhasker, C. R., Cox, T. C., Bottomley, S. S.,
27
28 1995. Molecular regulation of heme biosynthesis in higher vertebrates. *Prog. Nucleic*
29
30 *Acid Res. Mol. Biol.* 51, 1-51.
31
32

33
34 McCoubrey, W. K., Cooklis, M. A., Maines, M. D., 1995. The structure, organization and
35
36 differential expression of the rat gene encoding biliverdin reductase. *Gene* 160, 235-240.
37
38

39
40 McDonagh, A. F., 2001. Turning green to gold. *Nat. Struct. Biol.* 8, 198-200.
41
42

43
44 Mitchell, D.Y., Madhu, C., and Klaassen, C.D., 1990. Hepatotoxicants elevate serum
45
46 bilirubin by increasing formation not decreasing elimination of bilirubin. *Toxicol. Sci.* 10
47
48 (Suppl.), 61 (Abstract).
49
50

51
52 Morse, D., Choi, A. M., 2002. Heme oxygenase-1: the "emerging molecule" has arrived.
53
54 *Am. J. Respir. Cell Mol. Biol.* 27, 8-16.
55
56
57
58
59
60
61
62
63
64
65

Niittynen, M., Tuomisto, J. T., Auriola, S., Pohjanvirta, R., Syrjälä, P., Simanainen, U., Viluksela, M., Tuomisto, J., 2003. 2,3,7,8-Tetrachlorodibenzo-*p*-dioxin (TCDD)-induced accumulation of biliverdin and hepatic peliosis in rats. *Toxicol. Sci.* 71, 112-123.

Niittynen, M., Simanainen, U., Syrjälä, P., Pohjanvirta, R., Viluksela, M., Tuomisto, J., Tuomisto, J. T., 2007. Differences in acute toxicity syndromes of 2,3,7,8-tetrachlorodibenzo-*p*-dioxin and 1,2,3,4,7,8-hexachlorodibenzo-*p*-dioxin in rats. *Toxicology* 235, 39-51.

Okey, A. B., 2007. An aryl hydrocarbon receptor odyssey to the shores of toxicology: the Deichmann Lecture, International Congress of Toxicology-XI. *Toxicol. Sci.* 98, 5-38.

Peterson, R.E., Madhukar, B.V., Yang, K.H. and Matsumura, F., 1979. Depression of adenosine triphosphatase activities in isolated liver surface membranes of 2,3,7,8-tetrachlorodibenzo-*p*-dioxin-treated rats: correlation with effects on ouabain biliary excretion and bile flow. *J. Pharmacol. Exp. Ther.* 210, 275-282.

Pohjanvirta, R., 1990. TCDD resistance is inherited as an autosomal dominant trait in the rat. *Toxicol. Lett.* 50, 49-56.

Pohjanvirta, R., Niittynen, M., Lindén, J., Boutros, P. C., Moffat, I. D., Okey, A. B., 2006. Evaluation of various housekeeping genes for their applicability for normalization of mRNA expression in dioxin-treated rats. *Chem. Biol. Interact.* 160, 134-149.

Pohjanvirta, R., Tuomisto, J., 1994. Short-term toxicity of 2,3,7,8-tetrachlorodibenzo-*p*-dioxin in laboratory animals: effects, mechanisms, and animal models. *Pharmacol. Rev.* 46, 483-549.

1
2
3
4 Pohjanvirta, R., Unkila, M., Lindén, J., Tuomisto, J. T., Tuomisto, J., 1995. Toxic
5
6
7 equivalency factors do not predict the acute toxicities of dioxins in rats. Eur. J.
8
9 Pharmacol. 293, 341-353.
10
11
12 Pohjanvirta R., Unkila M., Tuomisto J., 1993. Comparative acute lethality of 2,3,7,8-
13
14 tetrachlorodibenzo-*p*-dioxin (TCDD), 1,2,3,7,8-pentachlorodibenzo-*p*-dioxin and
15
16
17 1,2,3,4,7,8-hexachlorodibenzo-*p*-dioxin in the most TCDD-susceptible and the most
18
19 TCDD-resistant rat strain. Pharmacol. Toxicol. 73, 52-56.
20
21
22
23 Pohjanvirta, R., Viluksela, M., Tuomisto, J. T., Unkila, M., Karasinska, J., Franc, M. A.,
24
25
26 Holowenko, M., Giannone, J. V., Harper, P. A., Tuomisto, J., Okey, A. B., 1999.
27
28
29 Physicochemical differences in the AH receptors of the most TCDD-susceptible and the
30
31 most TCDD-resistant rat strains. Toxicol. Appl. Pharmacol. 155, 82-95.
32
33
34 Pohjanvirta, R., Wong, J. M., Li, W., Harper, P. A., Tuomisto, J., Okey, A. B., 1998.
35
36
37 Point mutation in intron sequence causes altered carboxyl-terminal structure in the aryl
38
39 hydrocarbon receptor of the most 2,3,7,8-tetrachlorodibenzo-*p*-dioxin-resistant rat strain.
40
41
42 Mol. Pharmacol. 54, 86-93.
43
44
45 Poland, A., Glover, E., 1973. 2,3,7,8-Tetrachlorodibenzo-*p*-dioxin: a potent inducer of δ -
46
47 aminolevulinic acid synthetase. Science 179, 476-477.
48
49
50
51 Puga, A., Barnes, S. J., Chang, C., Zhu, H., Nephew, K. P., Khan, S. A., Shertzer, H. G.,
52
53
54 2000. Activation of transcription factors activator protein-1 and nuclear factor- κ B by
55
56 2,3,7,8-tetrachlorodibenzo-*p*-dioxin. Biochem. Pharmacol. 59, 997-1005.
57
58
59
60
61
62
63
64
65

1
2
3
4 Rigney, E., Mantle, T. J., 1988. The reaction mechanism of bovine kidney biliverdin
5 reductase. Biochim. Biophys. Acta. 957, 237-242.
6
7

8
9
10 Rigney E., Mantle T.J., Dickinson F.M., 1989. The kinetics of ox kidney biliverdin
11 reductase in the pre-steady state. Evidence that the dissociation of bilirubin is the rate-
12 determining step. Biochem. J. 259, 709-713.
13
14
15

16
17
18 Ryter, S. W., Choi, A. M., 2002. Heme oxygenase-1: molecular mechanisms of gene
19 expression in oxygen-related stress. Antioxid. Redox. Signal. 4, 625-632.
20
21
22

23
24 Senft, A. P., Dalton, T. P., Nebert, D. W., Genter, M. B., Hutchinson, R. J., Shertzer, H.
25 G., 2002. Dioxin increases reactive oxygen production in mouse liver mitochondria.
26 Toxicol. Appl. Pharmacol. 178, 15-21.
27
28
29

30
31
32 Shibahara S., 2003. The heme oxygenase dilemma in cellular homeostasis: new insights
33 for the feedback regulation of heme catabolism. Tohoku J. Exp. Med. 200, 167-186
34
35
36

37
38 Simanainen, U., Tuomisto, J. T., Tuomisto, J., Viluksela, M., 2002. Structure-activity
39 relationships and dose responses of polychlorinated dibenzo-*p*-dioxins for short-term
40 effects in 2,3,7,8-tetrachlorodibenzo-*p*-dioxin-resistant and -sensitive rat strains. Toxicol.
41 Appl. Pharmacol. 181, 38-47.
42
43
44
45
46

47
48
49 Srivastava, G., Borthwick, I. A., Maguire, D. J., Elferink, C. J., Bawden, M. J., Mercer, J.
50 F., May, B. K., 1988. Regulation of 5-aminolevulinate synthase mRNA in different rat
51 tissues. J. Biol. Chem. 263, 5202-5209.
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4 Stohs, S. J., 1990. Oxidative stress induced by 2,3,7,8-tetrachlorodibenzo-*p*-dioxin
5
6 (TCDD). Free Radic. Biol. Med. 9, 79-90.
7
8
9
10 Stohs, S. J., Shara, M. A., Alsharif, N. Z., Wahba, Z. Z., Al-Bayati, Z. A., 1990. 2,3,7,8-
11
12 Tetrachlorodibenzo-*p*-dioxin-induced oxidative stress in female rats. Toxicol. Appl.
13
14 Pharmacol. 106, 126-135.
15
16
17
18 Suzuki, T., Takahashi, T., Yamasaki, A., Fujiwara, T., Hirakawa, M., Akagi, R., 2000.
19
20 Tissue-specific gene expression of heme oxygenase-1 (HO-1) and non-specific δ -
21
22 aminolevulinate synthase (ALAS-N) in a rat model of septic multiple organ dysfunction
23
24 syndrome. Biochem. Pharmacol. 60, 275-283.
25
26
27
28
29 Tuomisto, J. T., Viluksela, M., Pohjanvirta, R., Tuomisto, J., 1999. The AH receptor and
30
31 a novel gene determine acute toxic responses to TCDD: segregation of the resistant
32
33 alleles to different rat lines. Toxicol. Appl. Pharmacol. 155, 71-81.
34
35
36
37
38 Unkila, M., Pohjanvirta, R., MacDonald, E., Tuomisto, J. T., Tuomisto, J., 1994. Dose
39
40 response and time course of alterations in tryptophan metabolism by 2,3,7,8-
41
42 tetrachlorodibenzo-*p*-dioxin (TCDD) in the most TCDD-susceptible and the most TCDD-
43
44 resistant rat strain: relationship with TCDD lethality. Toxicol. Appl. Pharmacol. 128,
45
46 280-292.
47
48
49
50
51 Yamamoto, M., Kure, S., Engel, J. D., Hiraga, K., 1988. Structure, turnover, and heme-
52
53 mediated suppression of the level of mRNA encoding rat liver δ -aminolevulinate
54
55 synthase. J. Biol. Chem. 263, 15973-15979.
56
57
58
59
60
61
62
63
64
65

1
2
3
4 Yang K.H., Yoo B.S., Choe S.Y., 1983. Effects of halogenated dibenzo-*p*-dioxins on
5
6 plasma disappearance and biliary excretion of ouabain in rats. Toxicol. Lett. 15, 259-264.
7
8
9
10 Zinkl, J. G., Vos, J. G., Moore, J. A., Gupta, B. N., 1973. Hematologic and clinical
11
12 chemistry effects of 2,3,7,8-tetrachlorodibenzo-*p*-dioxin in laboratory animals.
13
14 Environ.Health Perspect. 5, 111-118.
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

LEGENDS TO THE TABLES

TABLE 1. The primers used in the study.

TABLE 2. Changes in body weight and liver appearance in the experimental groups.

LEGENDS TO THE FIGURES

FIG. 1. Heme biosynthetic and degradation pathways showing the enzymes whose mRNA or protein expression or enzymatic activity after TCDD exposure was studied (in bold). ALAS1 = δ -aminolevulinic acid synthetase 1, BVRA = biliverdin IX α reductase, HO-1 = heme oxygenase 1, UGT = UDP-glucuronosyltransferase. Asterisk (*) denotes a rate-limiting step.

FIG. 2. Effect of TCDD (mean \pm S.D.) on the hepatic mRNA expression (relative to GAPDH) of ALAS1, HO-1 and BVRA in female line A and line B rats 2-35 days after exposure ($n = 5-10$, except for line B day 32 where $n = 2$; S.D. is not shown for this group). TCDD dose was 300 μ g/kg. The number under the x -axis denotes the day post-exposure (C = control). C consists of control groups from time points 2 and 35 days (C2 = day-2 control; C35 = day-35 control). If C2 and C35 differed significantly from each other in t -test, they were kept separate; otherwise a pooled control (C) was used. CYP1A1 and CYP1A2 were used as positive controls of induction. The asterisks denote differences from the control at the level of $p < 0.05$ (*), $p < 0.01$ (**) and $p < 0.001$ (***). Note the logarithmic scale in the graphs for CYP1A1.

FIG. 3. Effect of TCDD (mean \pm S.D.) on the splenic mRNA expression (relative to β -actin) of ALAS1, HO-1 and BVRA in female line A and line B rats. Experimental conditions and symbols are as in Fig. 2.

FIG. 4. Effect of TCDD (mean \pm S.D.) on hepatic and splenic mRNA expression (relative to GAPDH and β -actin, respectively) of ALAS1, HO-1 and BVRA in male L-E rats ($n = 6$). The rats were given 100 μ g/kg of TCDD and studied 10 days later. FR = feed-restricted control. The asterisks denote differences from the control at the level of $p < 0.05$ (*), $p < 0.01$ (**) and $p < 0.001$ (***). Note the logarithmic scale in the graph for CYP1A1.

FIG. 5. Effect of TCDD (300 μ g/kg; mean \pm S.D.) on hepatic and splenic HO-1 protein levels in female line A and line B rats 2 - 35 days after exposure ($n = 4-5$, except for line B, day 32, where $n = 2$; S.D. is not shown for this group). Symbols are as in Fig. 2.

FIG. 6. Effect of TCDD (300 μ g/kg; mean \pm S.D.) on hepatic BVRA activity in female line A and line B rats 2 - 35 days after exposure (A and B; $n = 5-12$ except for line B, day 32, where $n = 2$). Symbols are as in Fig. 2. The blank rate (before the addition of NADPH) is also presented (C and D). (*Blank rate* is the rate detected in a solution consisting of buffer + biliverdin + cytosol; *BVRA activity* is the rate detected after the addition of NADPH [100 μ M] into the reaction solution.)

TABLE 1.

Gene	GenBank	Forward primer	Reverse primer	Size of product (bp)
	Accession No.	(5'-3')	(5'-3')	
<i>ALAS1</i>	J03190	GCGCAATGTCAAGCTTATGA	TGGGTAATTAATGGCCTGGA	169
<i>HO-1</i>	J02722	CACAAAGACCAGAGTCCCTCA	AGAAAAGAGAACCCAGGCAAG	284
<i>BVRA</i>	NM-053850	CATGTCCTCGTGGAATACCC	AGCTGTGAAGCGAAGAGACC	186
<i>CYP1A1</i>	NM-012540	CCATATGCTTTGGCAGACGTTA	TCAAACCCAGCTCCAAAGAG	361
<i>CYP1A2</i>	NM-012541	TGATAACTTTGTGCTGTTTCTGC	GGTTGACCTGCCACTGGTTTA	473
<i>β-Actin</i>	NM-031144	CACGGCATTGTAACCAACTG	GAGCGCGTAACCCTCATAGA	297
<i>GAPDH</i>	NM-017008	ATCCCGCTAACATCAAATGG	GTGGTTCACACCCATCACAA	170

TABLE 2.

Group	Experiment	Body weight change ^a	Changes in liver appearance compared with control
Line A, 2-day control	I	-0.9 ± 1.8 %	
Line A, 35-day control	I	5.3 ± 3.1 %	
Line A, TCDD 300 µg/kg, 2 days	I	-1.3 ± 1.0 %	
Line A, TCDD 300 µg/kg, 7 days	I	-6.1 ± 2.6 %	
Line A, TCDD 300 µg/kg, 14 days	I	-7.2 ± 3.0 %	
Line A, TCDD 300 µg/kg, 35 days	I	-0.2 ± 2.9 %	Yellowish liver in 5 out of 6 rats.
Line B, 2-day control	I	1.8 ± 1.3 %	
Line B, 35-day control	I	6.2 ± 4.2 %	
Line B, TCDD 300 µg/kg, 2 days	I	-1.5 ± 1.4 %	
Line B, TCDD 300 µg/kg, 7 days	I	-15.6 ± 4.7 %	
Line B, TCDD 300 µg/kg, 14 days	I	-15.2 ± 5.4 %	
Line B, TCDD 300 µg/kg, 32 days	I	-11.5 ± 3.1 %	Dark green/black liver in 4 out of 7 rats.
L-E, control, 10 days	II	4.3 ± 3.0 %	
L-E, TCDD 100 µg/kg , 10 days	II	-31.6 ± 2.2 %	
L-E, feed-restricted control, 10 days	II	-18.7 ± 3.2 %	

^a Percent of initial body weight (mean ± S.D.).

FIG. 1.

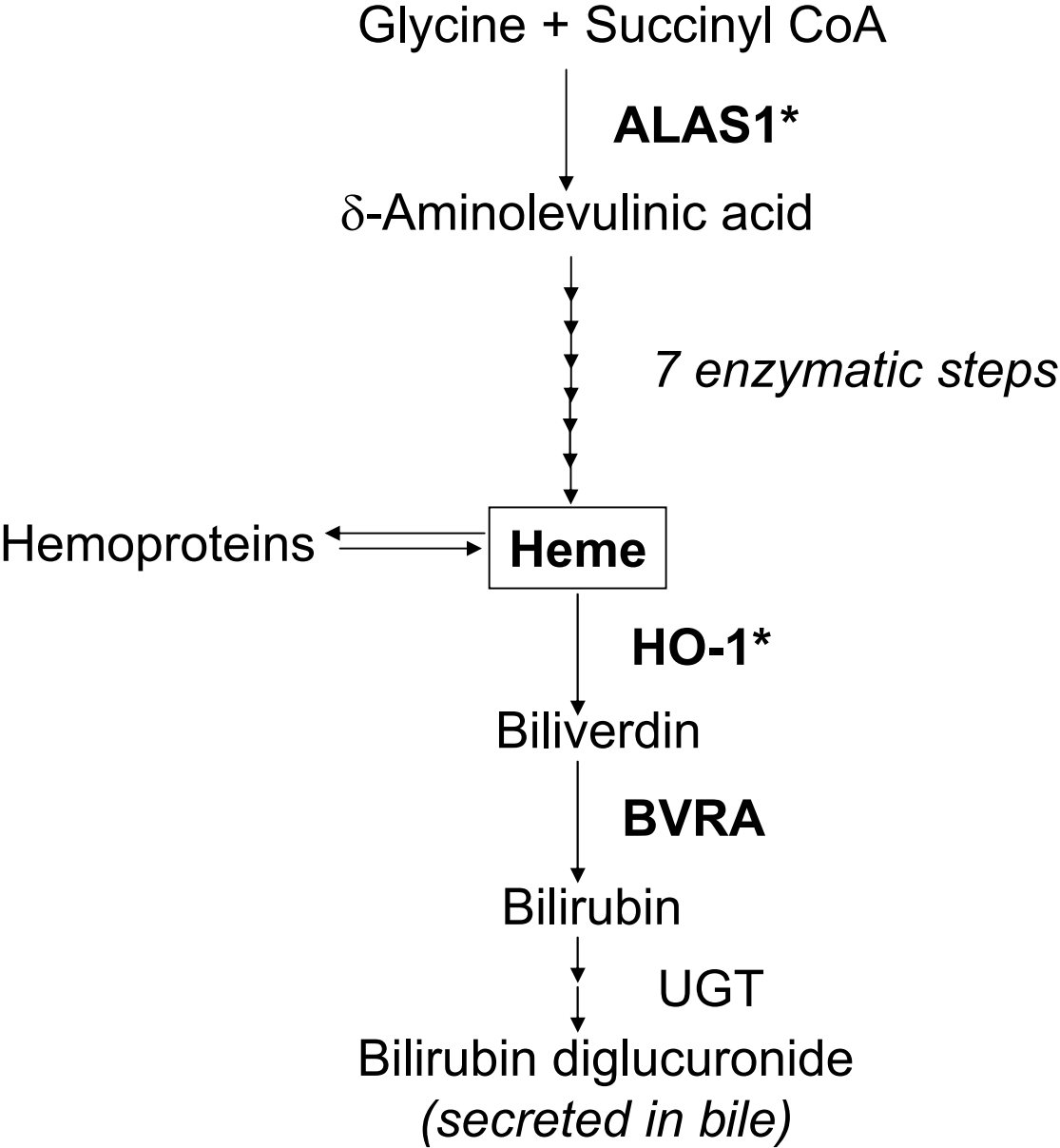


Figure
Click here to download Figure: Figure2.doc
FIG. 2.

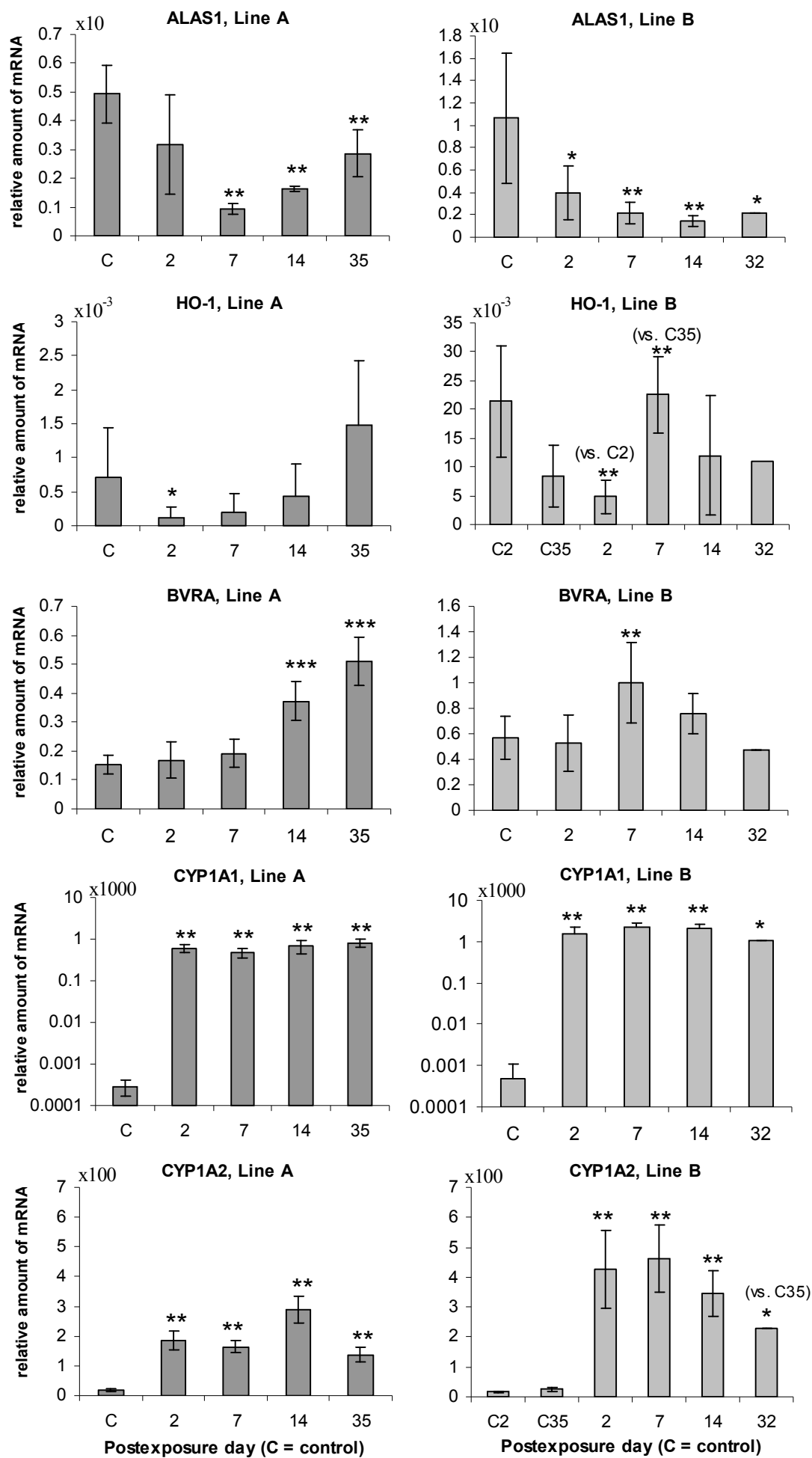


FIG. 3

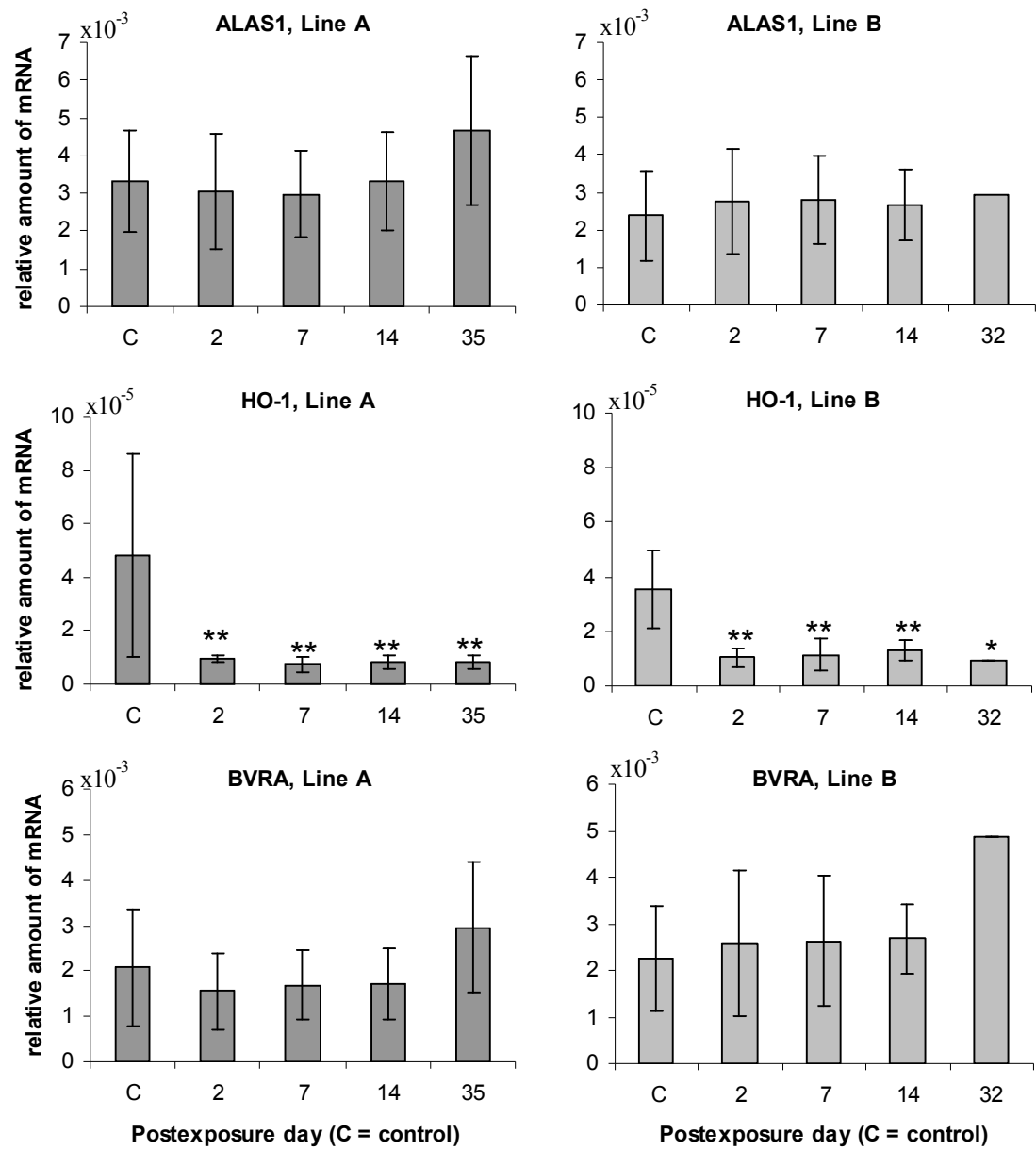


FIG. 4

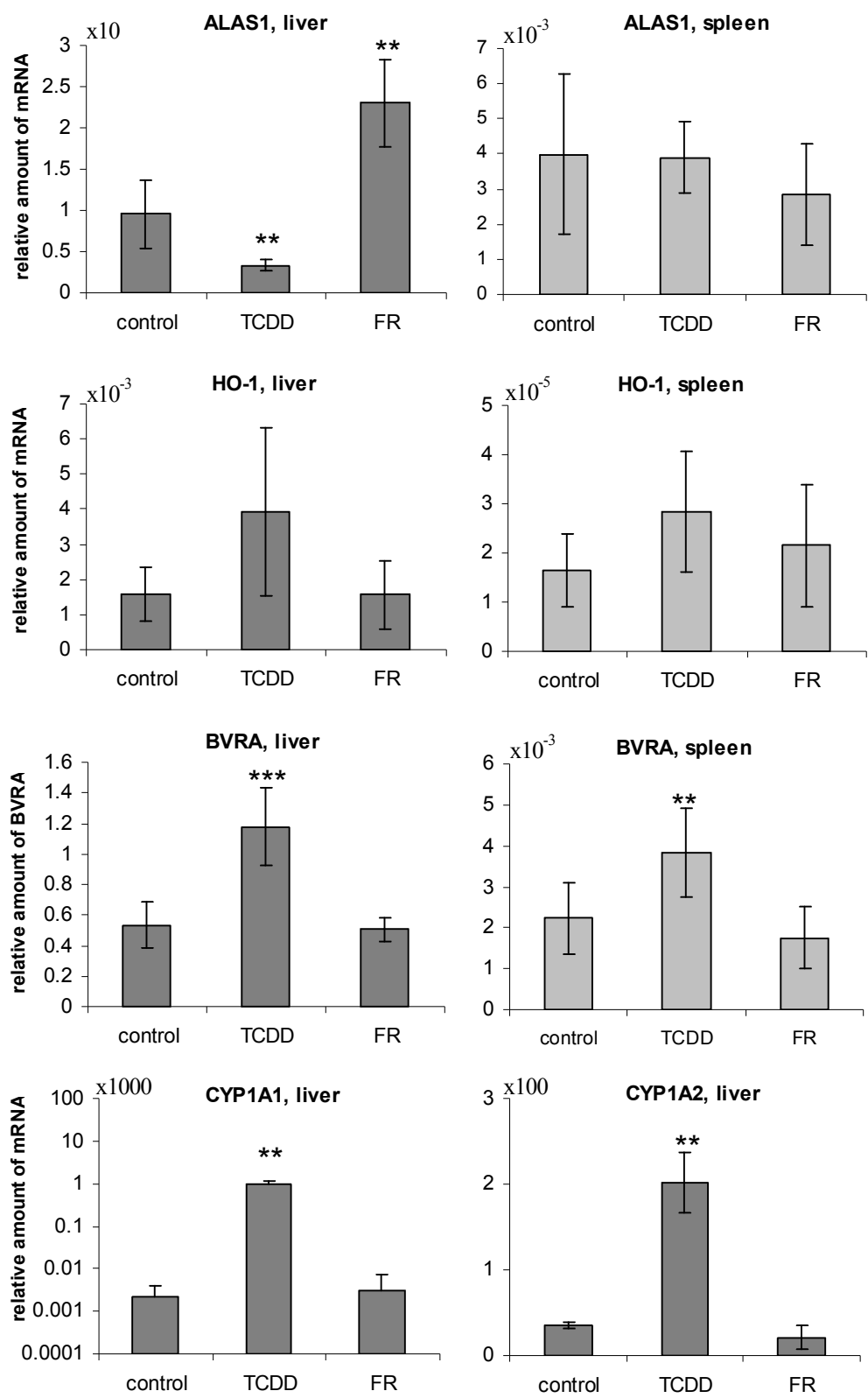


FIG. 5

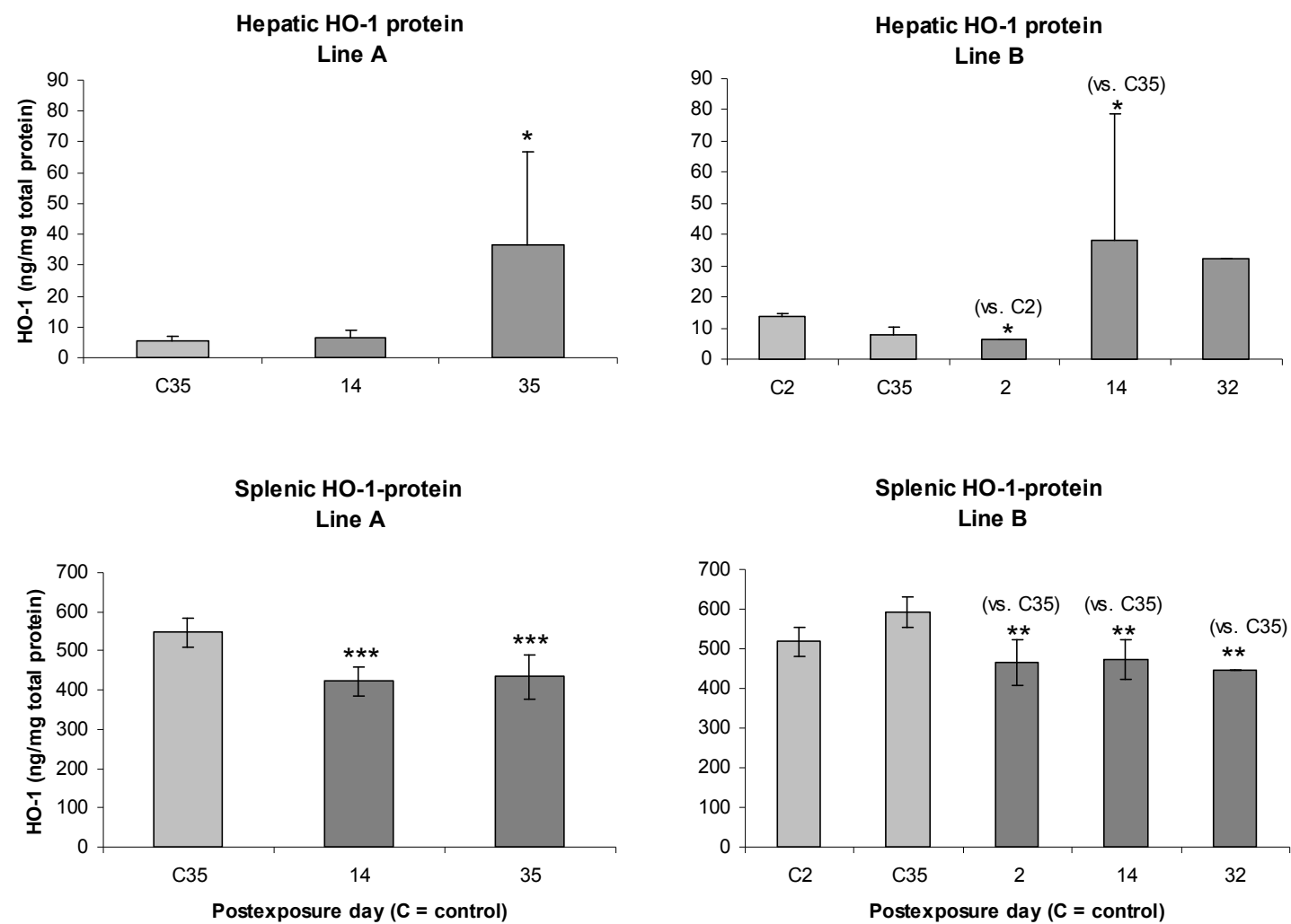
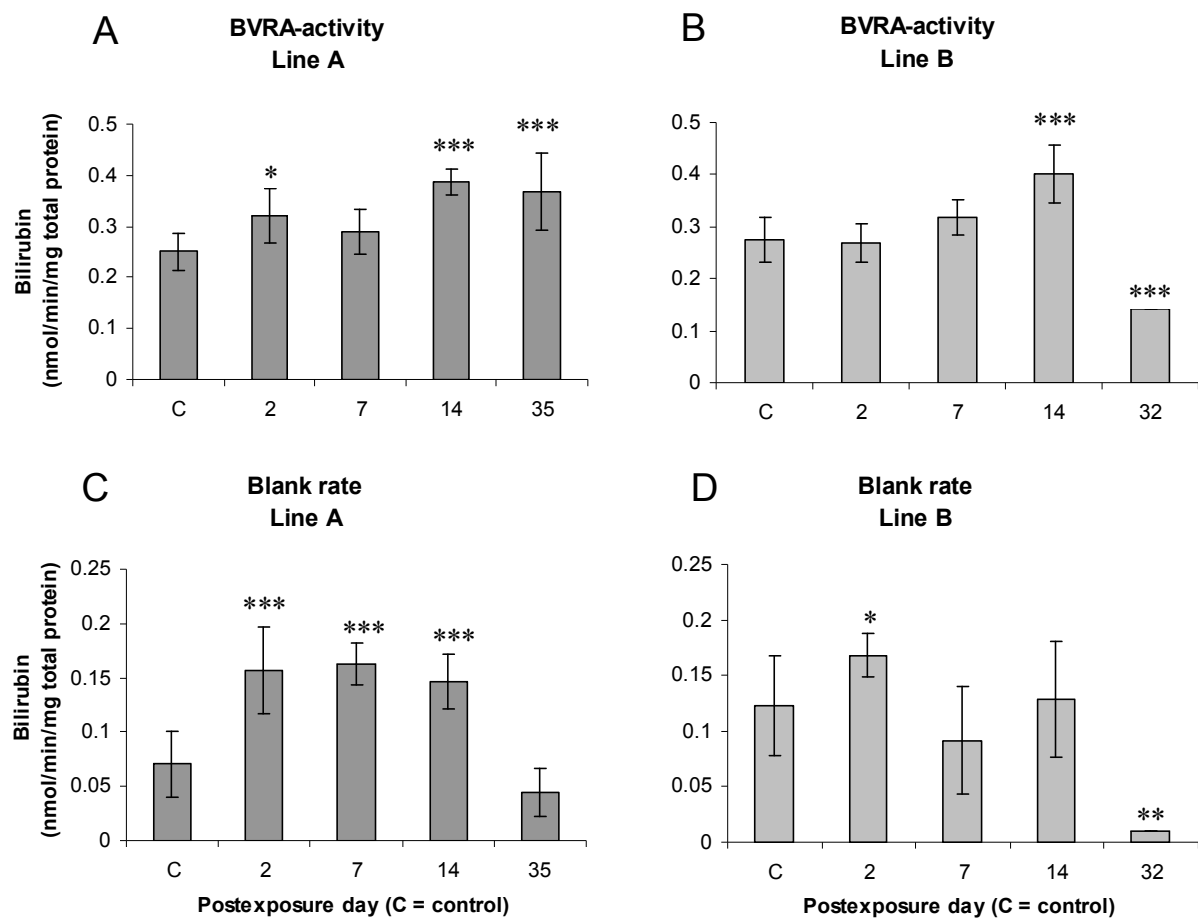
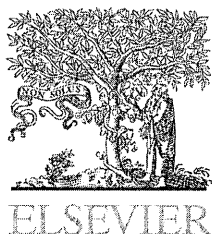


FIG. 6





Toxicology
Conflict of Interest Policy

Manuscript number (if applicable): -

Article Title: Effect of 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD) on heme oxygenase-1, biliverdin IX α reductase and δ -aminolevulinic acid synthetase 1 in rats with wild-type or variant AH receptor

Author name: Marjo Niittynen

Declarations

Toxicology requires that all authors sign a declaration of conflicting interests. If you have nothing to declare in any of these categories then this should be stated.

Conflict of Interest

Please declare any financial or personal interests that might be potentially viewed to influence the work presented. Interests could include consultancies, honoraria, patent ownership or other. If there are none state 'there are none'.

Please state any competing interests

There are none.

Funding Source

All sources of funding should be acknowledged and you should declare any extra funding you have received for academic research of this work. If there are none state 'there are none'.

Please state any sources of funding for your research

Academy of Finland, grant 53307
Emil Aaltonen Foundation
Finnish Cultural Foundation
Graduate School in Environmental Health SYTYKE

Signature (a scanned signature is acceptable, but each author must sign)

Print name

Marjo Niittynen



Toxicology
Conflict of Interest Policy

Manuscript number (if applicable): -

Article Title: Effect of 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD) on heme oxygenase-1, biliverdin IX α reductase and δ -aminolevulinic acid synthetase 1 in rats with wild-type or variant AH receptor

Author name: Jouni T
Tuomisto

Declarations

Toxicology requires that all authors sign a declaration of conflicting interests. If you have nothing to declare in any of these categories then this should be stated.

Conflict of Interest

Please declare any financial or personal interests that might be potentially viewed to influence the work presented. Interests could include consultancies, honoraria, patent ownership or other. If there are none state 'there are none'.

Please state any competing interests

There are none.

Funding Source

All sources of funding should be acknowledged and you should declare any extra funding you have received for academic research of this work. If there are none state 'there are none'.

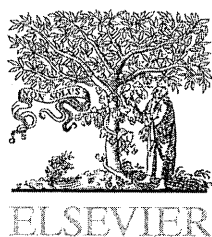
Please state any sources of funding for your research

Academy of Finland, grant 53307

Signature (a scanned signature is acceptable, but each author must sign)

Print name

Jouni T. Tuomisto



Toxicology
Conflict of Interest Policy

Manuscript number (if applicable): -

Article Title: Effect of 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD) on heme oxygenase-1, biliverdin IX α reductase and δ -aminolevulinic acid synthetase 1 in rats with wild-type or variant AH receptor

Author name: Raimo Pohjanvirta

Declarations

Toxicology requires that all authors sign a declaration of conflicting interests. If you have nothing to declare in any of these categories then this should be stated.

Conflict of Interest

Please declare any financial or personal interests that might be potentially viewed to influence the work presented. Interests could include consultancies, honoraria, patent ownership or other. If there are none state 'there are none'.

Please state any competing interests

There are none.

Funding Source

All sources of funding should be acknowledged and you should declare any extra funding you have received for academic research of this work. If there are none state 'there are none'.

Please state any sources of funding for your research

Academy of Finland, grant 211120 and 123345

Signature (a scanned signature is acceptable, but each author must sign)

Print name

Raimo Pohjanvirta