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Effect of tributyltin on mammalian endothelial cell integrity

This is the final peer-reviewed author's accepted manuscript (postprint) of the following publication:

Published Version:

Botelho, G., Bernardini, C., Zannoni, A., Ventrella, V., Bacci, M.L., Forni, M. (2015). Effect of tributyltin on mammalian endothelial cell integrity. *COMPARATIVE BIOCHEMISTRY AND PHYSIOLOGY. C. TOXICOLOGY & PHARMACOLOGY*, 176-177, 79-86 [10.1016/j.cbpc.2015.07.012].

Availability:

This version is available at: <https://hdl.handle.net/11585/525483> since: 2015-12-18

Published:

DOI: <http://doi.org/10.1016/j.cbpc.2015.07.012>

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This is the final peer-reviewed accepted manuscript of:

G. Botelho, C. Bernardini, A. Zannoni, V. Ventrella, M.L. Bacci, M. Forni, *Effect of tributyltin on mammalian endothelial cell integrity*, Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology, Volumes 176–177, 2015, Pages 79-86, ISSN 1532-0456

The final published version is available online at:

<https://doi.org/10.1016/j.cbpc.2015.07.012>

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1 REVIEW

2 EFFECT OF TRIBUTYL TIN ON MAMMALIAN ENDOTHELIAL CELL INTEGRITY

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25

26 **Abstract**

27

28 Tributyltin (TBT), is a man-made pollutants, known to accumulate along the food chain, acting as
29 an endocrine disruptor in marine organisms, with toxic and adverse effects in many tissues
30 including vascular system. Based on the absence of specific studies of TBT effects on endothelial
31 cells, we aimed to evaluate the toxicity of TBT on primary culture of porcine aortic endothelial cells
32 (pAECs), being pig an excellent model to study human cardiovascular disease. pAECs were
33 exposed for 24h to TBT (100, 250, 500, 750 and 1000nM) showing a dose dependent decrease in
34 cell viability through both apoptosis and necrosis. Moreover the ability of TBT (100 and 500nM) to
35 influence endothelial gene expression was investigated at 1, 7 and 15h of treatment. Gene
36 expression of tight junction molecules, occludin (OCLN) and tight junction protein-1 (ZO-1) was
37 reduced while monocyte adhesion and adhesion molecules ICAM-1 and VCAM-1 (intercellular
38 adhesion molecule-1 and vascular cell adhesion molecule-1) levels increased significantly.at 1
39 hour. IL-6 and estrogen receptors 1 and 2 (ESR-1 and ESR-2) mRNAs, after a transient decrease,
40 reached the maximum levels after 15h of exposure. These findings indicate that TBT deeply alter
41 endothelial profile, disrupting their structure and interfering with their ability to interact with
42 molecules and other cells.

43

44 **Keywords:** adhesion molecules, endothelial cells, estrogen receptors, inflammation, tight
45 junctions, Tributyltin

46

47 **Abbreviations:** porcine Aortic endothelial Cells (pAECs), tributyltin (TBT), occludin (OCLN), tight
48 junction protein-1 (ZO-1) intercellular adhesion molecule-1 (ICAM-1) vascular cell adhesion
49 molecule-1 (VCAM-1), interleukin-6 (IL-6) , estrogen receptors 1 and 2 (ESR-1 and ESR-2)

50

51

52

53 **1 Introduction**

54

55 Among man-made pollutants, known to accumulate along the food chain, organotins, and
56 mainly trisubstituted tin compounds, are especially dangerous, due to their wide industrial
57 exploitation as polyvinyl chloride stabilizers, catalysts, pesticides and biocides in antifouling paints.

58 Tributyltin (TBT) interact by both covalent and non-covalent bonds with biomolecules and
59 membrane structures and is considered among the most toxic substances ever deliberately
60 introduced into environment (Pagliarani et al. 2013).

61 In spite of bans of TBT use (IMO 2001), the residue in marine environment is still an
62 important concern (Horiguchi, 2012) due to its environmental persistence (Hoch, 2001; Fent et al,
63 2004). The contamination of aquatic environments is especially harmful. Bioaccumulation in
64 tissues of exposed species (Frouin et al., 2010) leads to contamination of seafoods (Ma et al.
65 2011) and in turn, mainly through the food chain, of terrestrial species including human (Kannan et
66 al., 1999; Takahashi et al., 1999).

67 TBT exerts a toxic effect acting as a classical endocrine disruptor for marine organisms
68 causing imposex in gastropod mollusks (Gallo and Tosti, 2013). TBT shows also toxic and adverse
69 effects in many kinds of cells and tissues of a variety of species, including mammalian (Ohshima et
70 al., 2005) in which affects endocrine system through different pathway. Organotins are potent
71 inhibitors of 11 β -hydroxysteroid dehydrogenase type-2 (11 β -HSD2) (Atanasov et al., 2005) and
72 shows proadipogenic activity in some cell lineages like human and mouse multipotent stromal stem
73 cells (Kirchner et al. 2010; Li et al., 2011; Penza et al., 2011).

74 Different cell types have depicted dissimilar levels of tolerance to TBT, resulting in a
75 diversity of effects and in specific toxic concentrations for every cell lineage. In a cultured human
76 granulosa-like tumor cell line, Saitoh et al. (2001) found a toxic TBT concentration of 1000 ng/mL,
77 causing cell death within 24h, while 200 ng/mL induced apoptosis of the cells. In neurons
78 continuously exposed to TBT for 3 days, Yamada et al. (2010) observed a TBT-induced death at
79 30 nM in 4-6 days cultures and at 50 nM in 14-16 days cultures, which means that older neurons

80 are more resistant to TBT toxicity. Significant loss of viability was observed in neuroblastoma cells
81 incubated for 24h with doses of TBT ranging from 250 nM onward, with a linearity found between
82 250 nM and 2 μ M (Ferreira et al., 2013) and in a Sertoli-germ cell co-culture incubated for 6h with
83 a minimum dose of 300 nM (Mitra et al., 2013a).

84 The information on human exposure to butyltin compounds is limited; some studies found
85 TBT, DBT(Dibutyltin), and MBT (Monobutyltin) levels in human tissues in the range of 3-100 nM
86 (Kannan et al., 1999; Takahashi et al., 1999). Butyltin compounds were already found in human
87 blood in concentrations ranging between 64 and 155 ng/mL (Whalen et al., 1999), in particular TBT
88 have been found up to 261 nM. This variability could be related to human diet, food habits, gender
89 and physiological stage which should be taken into account; controlled trial in animal models could
90 overcome this problem.

91 Recently, very interesting studies, using rodent model, correlated TBT to cardiovascular
92 disorders impairing the coronary vascular reactivity response to estradiol and producing endothelial
93 denudation in isolated rat heart (Dos Santos et al., 2012) and demonstrated TBT ability to reduce
94 vasoconstrictor response in isolated aortic rings of female rats (Rodrigues et al., 2014).

95 Among cellular components of vasculature, the endothelium is especially susceptible to
96 plasma toxicants because it is structurally arranged in a single layer of cells that first come into
97 contact with blood vessel contents. Further, injuries to endothelial cells are implicated in the
98 pathophysiology of several diseases (Yamada et al., 2011) and in particular in the cardiovascular
99 ones (Mordi and Tzemos, 2014).

100 Based on the recent demonstration that TBT can influence vascular system and on the
101 absence of specific studies of TBT effects on endothelial cells, we aimed to evaluate the toxicity of
102 TBT on mammalian endothelial cells, using primary cultures of porcine Aortic Endothelial Cells
103 (pAECs), being swine an excellent animal model in the field of cardiovascular research (Forni et
104 al., 2005; Vilahur et al., 2011; Zaragoza et al., 2011; Zannoni et al., 2012; Gessaroli et al., 2012).
105 In addition, we aimed to investigate the ability of TBT to influence gene expression of markers
106 involved in structure and function maintenance and in response to injuries of endothelial cells., in

107 and in estrogen sensitivity. Finally we evaluate the alteration of endothelial function induced by
108 TBT through monocytes adhesion assay.

109

110

111 **2 Materials and methods**

112

113 2.1 Chemicals and reagents

114 Human endothelial SFM medium, Heat inactivated FBS (fetal bovine serum) and Fungizone were
115 purchased from Gibco-Life technologies. Trypsin-EDTA solution 1X, Dimethyl sulphoxide (DMSO)
116 and tributyltin chloride (TBT) were from Sigma-Aldrich and Dulbecco's phosphate buffered saline
117 (DPBS) from EuroClone. AlexaFluor 488 annexin/dead cell apoptosis kit (Molecular Probes,
118 Eugene, USA Invitrogen) and CytoTox 96 Non-radioactive Cytotoxicity Assay (Promega. Promega
119 Corporation 2800 Woods Hollow Road Madison, WI 53711 USA) were used. NucleoSpin RNA kit
120 (Macherey-Nagel GmbH & Co. KG Postfach 10 13 52 D-52313 Düren Germany) was used for
121 RNA isolation and IScript cDNA synthesis kit, IQ Supermix and IQ SyBR Green Supermix.(Bio-Rad
122 Laboratories Inc., Hercules, CA, USA) were used for cDNA synthesis and RT-PCR analysis.

123

124 2.2 Cell culture

125 pAECs were isolated and maintained as previously described by Bernardini and colleagues (2005)
126 and used from the third to the sixth passage. The first seeding after thawing was always performed
127 in T-25 tissue culture flasks (3×10^5 cells/flask) (T25-Falcon, Beckton-Dickinson, Franklin Lakes, NJ,
128 USA) and successive experiments were conducted in 24-well (qPCR analysis and monocyte
129 adhesion assay) or 96-well assay plates (cell viability) (Falcon Beckton-Dickinson) with confluent
130 cultures. Cells were cultured in Human endothelial SFM medium, added with FBS (5%) and
131 antimicrobial/antimycotic solution (1x Gibco-Life technologies code 15240-062) at 38.5°C. The
132 tributyltin chloride was diluted in DMSO until a 5mM solution and therefore in culture medium to
133 obtain desired concentrations for cell exposure.

134

135 2.3 Cell Viability

136 The ability of TBT to induce cytotoxicity was evaluated by the CytoTox 96 Non-Radioactive
137 Cytotoxicity Assay (Promega BioSciences LLC San Luis Obispo, CA, USA) that quantitatively
138 measures lactate dehydrogenase (LDH), a stable cytosolic enzyme that is released upon cell lysis.

139 Confluent pAECs were incubated for 24h in a 96 well plate with TBT (0, 100, 250, 500, 750,
140 1000 nM) and the supernatant was collected to be analysed. The maximum LDH activity was
141 assessed by lysing cells, collecting the resulting medium and processing it as other samples.
142 Briefly, supernatant was incubated with a reconstructed substrate mix for 30 min at room
143 temperature, protected from light. Then, a stop solution was added and the absorbance was
144 recorded at 490 nm. Cytotoxicity of TBT was calculated according to the equation:

145 $\% \text{ Cytotoxicity} = \text{Experimental LDH release (OD 490)} / \text{Maximum LDH release (OD 490)}$.

146 To determine the ability of TBT to induce apoptosis or necrosis the Annexin V binding
147 assay was employed. This assay detect phosphatidilserine (PS) externalization on the plasma
148 membrane.

149 In viable cells PS is located on the cytoplasmic surface of the cell membrane. However during the
150 early stage of apoptosis, PS is translocated from the inner to the outer leaflet of the plasma
151 membrane.

152 Confluent pAECs cultures were incubated in a 24 well plate with increasing doses TBT and
153 the Annexin V / PI binding assay (Alexa Fluor® 488, Life Technologies) was used.

154 Cells were harvested, placed in eppendorf tubes, centrifuged at 500 x g for 10 min and
155 resuspended in 100 µL of Annexin binding buffer. Annexin V-FITC (5µL) and Propidium Iodide (1
156 µL) were added to cell suspension. After incubation, the cells were analyzed with a flow cytometer
157 (FACSAria; BD Biosciences) by collecting at least 10⁴ events.

158

159 2.4 RNA isolation and quantitative real time PCR (qPCR)

160 To determine the ability of TBT to influence endothelial gene expression, confluent pAECs were
161 incubated for different time (1, 7, 15 hours) with different doses of TBT (0, 100 or 500nM).
162 Total RNA was isolated using the NucleoSpin®RNA Kit (Macherey-Nagel GmbH & Co. KG,
163 Germany), and one µg of total high quality RNA (A_{260}/A_{280} ratio above 2.0) was reverse-transcribed
164 to cDNA using the iScript cDNA Synthesis Kit (Bio-RAD Laboratories Inc., California, USA) in a
165 final volume of 20 µL. Swine primers were designed using Beacon Designer 2.07 (Premier Biosoft
166 International, Palo Alto, CA, USA) for each studied gene: estrogen receptor 1 and 2 (ER-1; ER-2);
167 tight junction proteins: occludin (OCLN) and tight junction protein-1 (ZO-1); adhesion molecules:
168 vascular cell adhesion molecule-1 (VCAM-1) and intercellular adhesion molecule-1 (ICAM-1);
169 cytokine: interleukine-6 (IL-6). Moreover, primers for the following reference genes glyceraldehyde-
170 3-phosphate dehydrogenase (GAPDH), β -actin and Hypoxanthine-guanine
171 phosphoribosyltransferase (HPRT-), were designed in order to evaluate the most suitable using
172 BestKeeper Software (Pfaffl et al., 2004) for qPCR normalization. Primer sequences, expected
173 PCR product lengths and accession numbers in the NCBI database are shown in Table 1.
174 Quantitative real-time PCR was performed to evaluate gene expression profiles in iCycler (Bio-
175 RAD) using SYBR green I detection system. The amplification reaction (25 µL) contained 12.5 µL
176 of IQ SYBER Green Bio-RAD Supermix (Bio-RAD), 1 µL of each forward and reverse primer (5
177 µM), 2.5 µL cDNA and 8 µL of water. All samples were performed in duplicate and controls lacking
178 cDNA template were included to determine the specificity of target amplification. The real-time
179 program included an initial denaturation for 1min 30s at 95°C, 40 cycles of 95°C for 15s, and 60°C
180 for 30s, followed by a melting step with ramping from 55°C to 95°C at a rate of 0.5°C/10s.
181 Specificity of the amplified PCR products was confirmed by melting curve analyses and agarose
182 gel electrophoresis. The expression level of interest genes was calculated as fold of increase using
183 $2^{-\Delta\Delta CT}$ method (Livak and Schmittgen, 2001) in relation to pAECs cultured under standard
184 conditions (control).

185 2.5 Monocytes adhesion assay

186 Separation of peripheral blood mononuclear cells (PBMC) was performed by Lympholyte-H
187 (Cedarlane, Burlington, NC, USA) following the instruction. PBMC were washed twice with PBS,
188 suspended in DMEM supplemented with 10% FBS and placed on a Petri dish for 1h at 38.5°C in a
189 humidified 5% CO₂ atmosphere to allow cells adhesion. Then, the culture medium containing non-
190 adherent cells was removed and medium was replaced. After 48h of culture, cells were detached
191 using a scraper and suspended in DMEM supplemented with 10% FBS (Cutini et al., 2012).

192 Monocytes adhesion assay was performed according to Lim et al. (2011). pAECs were treated with
193 TBT 0, 100 or 500 nM for 1h. Fresh culture medium containing 1.5x10⁴ PBMC was added in each
194 well and incubated for 2h at 38.5°C in a humidified 5% CO₂. Unbound cells were removed by
195 washing with PBS. PBMC adhering to pAEC layer were counted in 5 randomly selected fields for
196 each well.

197

198 2.6 Statistical analysis

199 All the data were analysed with the Shapiro-Wilk test, to assess whether they are modelled by a
200 normal distribution, and with the Levene test, to assess whether the variances are comparable.

201 Normal distribution of data and homoscedasticity were assumed, with *p* value > 0.05. Data
202 were analyzed through Students *t*-test comparing treatments in relation to the control. Statistical
203 analysis was carried out by using R software (<http://www.R-project.org>)

204

205

206 3 Results

207

208 3.1 Effect of TBT on cell viability

209 pAECs exposed to TBT lost gradually their typical morphology of continuous monolayer and an
210 increasing number of detached cells appeared related to the increase of TBT dose (Fig. 1A). The
211 loss of cells viability is demonstrated by LDH release: TBT induced significant decrease of cell
212 viability from the dose of 250nM (Fig 1B). The flow cytometric data showed that TBT is capable to

213 induce both apoptosis and necrosis (Fig 1C), even if apoptosis was prevalent at lower doses (data
214 not shown).

215

216 3.2 Effect of TBT on gene expression

217 The mRNA expression stability of the commonly used reference gene (GAPDH, HPRT, β -Actin)
218 revealed that β -actin expression was reduced after TBT exposure (data not shown). Therefore,
219 GAPDH and HPRT geometric mean value of Ct was used for normalization of qPCR data.

220 Both tight junction molecules OCLN and ZO-1 were lower in pAECs treated respect to
221 pAECs under standard culture conditions starting from 7h of exposure at 500 nM TBT (Figure 2 B;
222 D); moreover ZO-1 expression showed significant decrease also at low dose (Fig. 2 C). The
223 adhesion molecules, VCAM-1 and ICAM-1 showed a significant transient increase at 1 hour at both
224 doses, followed by a decrease (Fig. 3).

225 IL-6 mRNA was transiently reduced at early times for both TBT doses. After 15h of exposure at
226 TBT 500 nM the IL-6 expression was significantly increased (Figure 4).

227 The transcript of both estrogen receptors was significantly decreased at both doses after 1
228 and 7 hours, then, at 15 hours, both receptors increased even if only ER-1 was significantly
229 increased with TBT 500 nM (Fig. 5).

230

231 3.3 Effect of TBT on monocyte adhesion

232 Increased monocyte adhesion was observed after TBT treatment the monocyte adhesion
233 assay (Fig 6), As shown in Fig 6C the TBT treatment significantly increased monocyte adhesion

234

235

236 **4 Discussion**

237 Among different cellular types, the endothelium, uniquely positioned at the interface
238 between the vessel wall and flowing blood, can be a relevant target for TBT toxic action. The
239 endothelial layer, in fact, regulates multiple functions such as maintenance of normal vascular

240 tone, modulation of coagulation, and immune responses (Maney et al., 2011) and may contribute
241 to vascular disorders (Aki et al., 2008). Therefore, being endothelial cells directly exposed to the
242 TBT accumulated in the bloodstream as a result of biomagnification, it is important to investigate in
243 which extent they are affected in relation to its principal features.

244 Our study demonstrated that TBT significantly reduced the viability of pAECs, displaying a
245 consistent dose-response relation. Accordingly, the cell death mechanism, namely apoptosis or
246 necrosis, is known to depend on the TBT dose and exposure time (Pagliarani et al.,2013). The
247 cytotoxic effect of TBT on pAECs was observed at 250nM dose, comparable to that one exhibited
248 in neuroblastoma cell (Ferreira et al., 2013). A great variability in cell susceptibility to TBT is
249 reported in the literature: mouse neurons exhibit signs of toxicity and death from concentrations of
250 30 nM (Yamada et al., 2010) while rat or trout hepatocytes begin to die from 2 μ M (Reader et al.
251 1999, Jurkiewicz et al., 2004).

252 The lowest dose utilized had no significant effects on cell viability, however, it had an
253 relevant effect on gene expression, this result is to be considered taking into account that in human
254 blood TBT was found till 155 ng/mL (Whalen et al., 1999).

255 Expression of genes related to tight junctions (OCLN and ZO-1) was reduced by TBT
256 exposure confirming the morphological alterations observed and consistently with an increased
257 number of round and detached cells. Therefore, from a functional point of view, TBT alters the
258 typical architecture of endothelial cell-cell junctions, consistently with previous reports in various
259 mammalian cell types such as epithelial cell *in vitro* (Tsukazaki et al., 2004) prostate cells *in vivo*
260 (Barthelemy et al., 2007) and isolated heart cells *ex vivo*(Dos Santos et al. 2012)

261 Adhesion molecules, responsible for mediating the aggregation of cells to endothelium, are
262 considered markers of endothelial dysfunction and are used to predict potential vascular risk
263 (Wiseman et al., 2014). VCAM-1 is constitutively expressed on endothelial cells and mediates
264 tethering and rolling of lymphocytes and monocytes (Tu et al., 2013). ICAM-1 is constitutively
265 expressed on the cell surface of endothelial cells and leukocytes and functionally activates
266 leukocyte-endothelial adhesion and migration. The effect of TBT on ICAM-1 and VCAM-1 gene

267 expression, in our model, followed the same trend with an initial increase and a subsequent
268 decrease, in accordance with the modification that occurs at the beginning of an endothelium
269 dysfunction. (Burger et al., 2012). Consistently, as adhesion molecules mediate the adherence of
270 circulating leukocytes to the vascular endothelium, TBT treatment strongly increased monocytes
271 adhesion to pAECs.

272 The response of endothelial cells to a toxic injury often involves several changes in
273 inflammatory mediators. IL-6 is a pleiotropic cytokine, it regulate B cell differentiation,
274 immunoglobulin production, T cell proliferation and participate to the regulation of inflammatory
275 responses driving adhesion molecules synthesis in endothelial cells (Fogam 2011). IL-6 is also a
276 potent proangiogenic cytokine regulating vascular endothelial growth factor (VEGF) secretion
277 (Nilsson et al., 2005; Pober et al., 2009); different cell types produce IL-6 among these endothelial
278 cells are one of the major sources of plasma IL-6 (Tanaka et al., 2011).

279 In our model, TBT was able to reduce IL-6 mRNA expression at early times for both doses.
280 However TBT 500nM strongly increased the IL-6 mRNA expression after 15h of treatment, in
281 accordance with data observed by Mitra et al. (2013) in neural dissociated cortical cells and likely
282 in an effort to induce cell survival through VEGF.

283 The interaction of organotin with nuclear receptors is well known, they augment
284 adipogenesis via the interaction with PPAR γ /RXR α (Grün and Blumberg, 2006) and inhibit
285 estrogen with a systemic action and/or through repression of ER synthesis (McAllister and Kime,
286 2003, Delfosse et al., 2014). The expression of the two estrogen genes receptors was altered by
287 TBT: the expression decreased till 7h at both doses, whilst a strong increase was observed after
288 15h only with the highest dose. Similarly, Zhang et al. (2013) shown that TBT affected the ERs
289 gene expression in males rockfish (*Sebastes marmoratus*) leading to an increase or a decrease
290 depending on the applied concentrations.

291 Further investigations will be necessary to clarify the functional impact of this estrogen
292 receptor alteration. The multiple effect of estrogens mediated by ERs includes endothelial
293 proliferation, endothelial apoptosis inhibition, modulation of adhesion molecules with an overall

294 protective effect against cardiovascular diseases (Mendelsohn and Karas 1999; Mosca et al.,
295 2011). In fact it is well know that the incidence of cardiovascular disease differs significantly
296 between man and woman being lower in man and in post-menopausal women.

297 Overall the exposure of endothelial cells to TBT induced a wide range of effects all
298 consistent with endothelial dysfunction that represents the first stage of many vascular diseases. in
299 In our model TBT induced a shifts from an anti- to a pro-adhesive endothelial phenotype that is the
300 first step of inflammatory process and an important risk factor for cardiovascular diseases (Aird,
301 2008). Moreover we demonstrate the alteration of cell-cell junctions that is known to be responsible
302 in vivo of alteration of permeability exiting in edema and vascular fragility (Dejana et al., 2009).

303 The role of ER in triggering the TBT effects on endothelial cells and, on turn, on
304 cardiovascular diseases, must be deeply investigated due to the clear protective effect that
305 estrogens exert on cardiovascular system and the power of TBT to alter steroidogenesis.

306 Therefore, further *in vivo* investigation using pig model will be necessary to understand the
307 pathological implication of TBT contamination in the development of cardiovascular alterations.

308

309

310

311 **Acknowledgments**

312

313 This work was supported by the essential contribution of “Fondazione del Monte di Bologna e
314 Ravenna”

315

316 **5 References**

317 Aird WC. 2008. Endothelium in health and disease. *Pharmacol Rep.* 60(1):139-43.

318

319 Aki, T., Egashira, N., Hama, M., Yamauchi, Y., yano, T., Itoh, Y., Oishi, R., 2008. Characteristics of
320 gabexate mesilate-induced cell injury in porcine aorta endothelial cells. *J Pharmacol Sci.* 106, 415-
321 422.

322

323 Atanasov, A.G., Nashev, L.G., Tam, S., Baker, M.E., Odermatt, A., 2005. Organotins disrupt the
324 11beta-hydroxysteroid dehydrogenase type-2-dependent local inactivation of glucocorticoids.
325 *Environ Health Perspect.* 113, 1600-1606.

326

327 Barthelemy, J., Addeko, A., Robaire, B., Cyr, D.G., 2007. In utero exposure to tributyltin alters the
328 expression of E-cadherin and localization of claudin-1 in intercellular junctions of the rat ventral
329 prostate. *Mol Reprod Dev.* 74, 455-467.

330

331 Bernardini, C., Zannoni, A., Turba, M.E., Fantinati, P., Tamanini, C., Bacci, M.L., Forni, M., 2005.
332 Heat shock protein 70, heat shock protein 32, and vascular endothelial growth factor production
333 and their effects on lipopolysaccharide-induced apoptosis in porcine aortic endothelial cells. *Cell*
334 *Stress Chaperones.* 10, 340-348.

335

336 Burger, D., Touys, R.M., 2012. Cellular biomarkers of endothelial health: microparticles, endothelial
337 progenitor cells, and circulating endothelial cells. *J Am Soc Hypertens.* 6, 85-99.

338

339 Celada, L.J., Whalen, M.M., 2013. Effects of butyltins on mitogen-activated-protein kinase and Ras
340 activity in human natural killer cells. *J Appl Toxicol.* Epub ahead of print.

341

342 Chen, J., Huang, C., Truong, L., La Du, J., Tilton, S.C., Waters, K.M., Lin, K., Tanguay, R.L., Dong,
343 Q., 2012. Early life stage trimethyltin exposure induces ADP-ribosylation factor expression and
344 perturbs the vascular system in zebrafish. *Toxicology*. 302, 129-139.

345

346 Cutini PH, Campelo AE, Agriello E, Sandoval MJ, Rauschemberger MB, Massheimer VL. The role
347 of sex steroids on cellular events involved in vascular disease. *J Steroid Biochem Mol Biol*. 2012
348 Nov;132(3-5):322-30.

349

350 Delfosse V, Maire AL, Balaguer P, Bourguet W. 2014. A structural perspective on nuclear
351 receptors as targets of environmental compounds. *Acta Pharmacol Sin*. Dec 15.

352

353 Dos Santos, R.L., Podratz, P.L., Sena, G.C., Filho, V.S., Lopes, P.F., Gonçalves, W.L., Alves,
354 L.M., Samoto, V.Y., Takiya, C.M., de Castro Miguel E., Moysés, M.R., Graceli, J.B., 2012.
355 Tributyltin impairs the coronary vasodilation induced by 17 β -estradiol in isolated rat heart. *J Toxicol*
356 *Environ Health A*. 75, 948-959.

357

358 Fent, K., 2004. Ecotoxicological effects at contaminated sites. *Toxicology*. 205, 223-240.

359

360 Ferreira, M., Blanco, L., Garrido, A., Vieites, J.M., Cabado, A.G., 2013. In vitro approaches to
361 evaluate toxicity induced by organotin compounds tributyltin (TBT), dibutyltin (DBT), and
362 monobutyltin (MBT) in neuroblastoma cells. *J Agric Food Chem*. 61, 4195-4203.

363

364 Fogal B, Yi T, Wang C, Rao DA, Lebastchi A, Kulkarni S, Tellides G, Pober JS. 2011. Neutralizing
365 IL-6 reduces human arterial allograft rejection by allowing emergence of CD161+ CD4+ regulatory
366 T cells. *J Immunol*. 187(12):6268-80.

367

368 Forni, M., Mazzola, S., Ribeiro, L.A., Pirrone, F., Zannoni, A., Bernardini, C., Bacci, M.L., Albertini,
369 M., 2005. Expression of endothelin-1 system in a pig model of endotoxic shock. *Regul Pept.* 131,
370 89-96.

371

372 Frouin, H., Pelletier, E., Lebeuf, M., Saint-Louis, R., Fournier, M., 2010. Toxicology of organotins in
373 marine organisms: a review. In: Chin, H.F. (Ed.), *Organometallic Compounds: Preparation,*
374 *Structure and Properties.* Nova Science Publishers Inc., New York, pp. 1–47.

375

376 Gallo, A., Tosti, E., 2013. Adverse effect of antifouling compounds on the reproductive
377 mechanisms of the ascidian *Ciona intestinalis*. *Mar Drugs.* 11, 3554-3568.

378

379 Gessaroli, M., Bombardi, C., Giunti, M., Bacci, M.L., 2012. Prevention of neointimal hyperplasia
380 associated with modified stretch expanded polytetrafluoroethylene hemodialysis grafts (Gore) in an
381 experimental preclinical study in swine. *J Vasc Surg.* 55, 192-202.

382

383 Grün F., Blumberg B. 2007. Perturbed nuclear receptor signaling by environmental obesogens as
384 emerging factors in the obesity crisis. *Rev. Endocr. Metab. Disord.*, 8 (2) : 161–171

385

386 Hoch. M., 2001. Organotin compounds in the environment-an overview. *Appl Geochem.* 16, 719-
387 743.

388

389 Horiguchi, T., 2012. Ecotoxicological impacts of organotins: an overview. In: Pagliarani, A.,
390 Trombetti, F., Ventrella, V. (Eds.), *Biochemical and Biological Effects of Organotins.* Bentham
391 Science Publishers, Sharjah, UAE, pp. 3–24.

392

393 International Maritime Organization (IMO). 2001. Adoption of the final act of the conference and
394 any instruments, recommendations and resolutions resulting from the work of the conference.

395 International Convention on the Control of Harmful Anti-fouling Systems on Ships, 2001
396 (AFS/CONF/26, 18 October 2001), London, UK. London:International Maritime Organization, 1–26.
397

398 Jurkiewicz, M., Averill-Bates, D.A., Marion, M., Denizeau, F., 2004. Involvement of mitochondrial
399 and death receptor pathways in tributyltin-induced apoptosis in rat hepatocytes. *Biochimica et*
400 *Biophysica Acta.* 1693, 15-27.
401

402 Kannan, K., Senthilkumar, K., Giesy, J.P., 1999. Occurrence of Butyltin Compounds in Human
403 Blood *Environ Sci Tech* 33, 1776-1779.
404

405 Kirchner, S., Kieu, T., Chow, C., Casey, S., Blumberg, B., 2010. Prenatal exposure to the
406 environmental obesogen tributyltin predisposes multipotent stem cells to become adipocytes. *Mol*
407 *Endocrinol.* 24, 526-539.
408

409 Kiszal, P., Makó, V., Prohászka, Z., Cervenak, L., 2007. Interleukin-6 -174 promoter polymorphism
410 does not influence IL-6 production after LPS and IL-1 beta stimulation in human umbilical cord vein
411 endothelial cells. *Cytokine.* 40, 17-22.
412

413 Li, X., Ycaza, J., Blumberg, B., 2011. The environmental obesogen tributyltin chloride acts via
414 peroxisome proliferator activated receptor gamma to induce adipogenesis in murine 3T3-L1
415 preadipocytes. *J Steroid Biochem Mol Biol.* 127, 9-15.
416

417 Lim S1, Yoon JW, Kang SM, Choi SH, Cho BJ, Kim M, Park HS, Cho HJ, Shin H, Kim YB, Kim HS,
418 Jang HC, Park KS. EGb761, a Ginkgo biloba extract, is effective against atherosclerosis in vitro,
419 and in a rat model of type 2 diabetes. *PLoS One.* 2011;6(6):e20301.
420

421 Livak, K.J., Schmittgen, T.D., 2001. Analysis of relative gene expression data using real-time
422 quantitative PCR and the 2(-Delta Delta C(T)) Method. *Methods*. 25, 402-408.

423

424 Ma, X., Lian, Q.Q., Dong, Q., Ge, R.S., 2011. Environmental inhibitors of 11 β -hydroxysteroid
425 dehydrogenase type 2. *Toxicology*. 285, 83-89.

426

427 Maney, S.K., Johnson, A.M., Sampath, Kumar A., Nair, V., Santhosh Kumar T.R., Kartha, C.C.,
428 2011. Effect of apoptosis-inducing antitumor agents on endocardial endothelial cells. *Cardiovasc*
429 *Toxicol.* 11, 253-262.

430

431 May L.T., Torcia G., Cozzolino F., Ray A., Tatter S.B., Santhanam U., Sehgal P.B., Stern D. 1989.
432 Interleukin-6 gene expression in human endothelial cells: RNA start sites, multiple IL-6 proteins
433 and inhibition of proliferation. *Biochem Biophys Res Commun*, 159:991–998

434

435 McAllister B.G., Kime D.E. 2003. Early life exposure to environmental levels of the aromatase
436 inhibitor tributyltin causes masculinisation and irreversible sperm damage in zebrafish (*Danio rerio*)
437 *Aquat. Toxicol.*, 65 (3): 309–316.

438

439 Mitra, S., Gera, R., Singh, V., Khandelwal, S., 2013. Comparative toxicity of low dose tributyltin
440 chloride on serum, liver, lung and kidney following subchronic exposure. *Food Chem Toxicol.*
441 [Epub ahead of print].

442

443 Mitra, S., Srivastava, A., Khandelwal, S., 2013. Tributyltin chloride induced testicular toxicity by
444 JNK and p38 activation, redox imbalance and cell death in sertoli-germ cell co-culture. *Toxicology.*
445 314, 39-50.

446

447 Mendelsohn, M.E., Karas, R.H., 2005. Molecular and cellular basis of cardiovascular gender
448 differences. *Science*. 308, 1583-1587.

449

450 Mordi, I., Tzemos, N., 2014. Is reversal of endothelial dysfunction still an attractive target in
451 modern cardiology? *World J Cardiol*. 6, 824-835.

452

453 Mosca, L., Barrett-Connor, E., Wenger, N.K., 2011. Sex/gender differences in cardiovascular
454 disease prevention: what a difference a decade makes. *Circulation*. 124, 2145-2154.

455

456 Nilsson MB, Langley RR, Fidler IJ. 2005. Interleukin-6, secreted by human ovarian carcinoma
457 cells, is a potent proangiogenic cytokine. *Cancer Res*. 65(23):10794-800.

458

459 Ohshima, M., Ohno, S., Nakajin, S., 2005. Inhibitory effects of some possible endocrine-disrupting
460 chemicals on the isozymes of human 11beta-hydroxysteroid dehydrogenase and expression of
461 their mRNA in gonads and adrenal glands. *Environ Sci*. 12, 219-230.

462

463 Pagliarani, A., Nesci, S., Ventrella, V., 2013. Toxicity of organotin compounds: shared and
464 unshared biochemical targets and mechanisms in animal cells. *Toxicol In Vitro*. 27, 978-990.

465

466 Penza, M., Jeremic, M., Marrazzo, E., Maggi, A., Ciana, P., Rando, G., Grigolato, P.G., Di
467 Lorenzo, D., 2011. The environmental chemical tributyltin chloride (TBT) shows both estrogenic
468 and adipogenic activities in mice which might depend on the exposure dose. *Toxicol Appl
469 Pharmacol*. 255, 65-75.

470

471 Pffaf, M.W., Tichopad, A., Prgomet, C., Neuvians, T.P., 2004. Determination of stable
472 housekeeping genes, differentially regulated target genes and sample integrity: BestKeeper-Excel-
473 based tool using pair-wise correlations. *Biotechnol Lett*. 26, 509-515.

474

475 Pober JS, Min W, Bradley JR.2009. Mechanisms of endothelial dysfunction, injury, and death.
476 *Annu Rev Pathol.* 4:71-95.

477

478 Reader, S., Moutardier, V., DenizEAU, F., 1999. Tributyltin triggers apoptosis in trout hepatocytes:
479 the role of Ca²⁺ protein kinase C and proteases. *Biochimica et Biophysica Acta.* 1448, 473-485.

480

481 Rodrigues, S.M., Ximenes, C.F., de Batista, P.R., Simões, F.V., Coser, P.H., Sena, G.C., Podratz,
482 P.L., de Souza, L.N., Vassallo, D.V., Graceli, J.B., Stefanon, I., 2014. Tributyltin contributes in
483 reducing the vascular reactivity to phenylephrine in isolated aortic rings from female rats. *Toxicol*
484 *Lett.* 225, 378-385.

485

486 Saitoh, M., Yanase, T., Morinaga, H., Tanabe, M., Mu, Y.M., Nishi, Y., Nomura, M., Okabe, T.,
487 Goto, K., Takayanagi, R., Nawata, H., 2001. Tributyltin or triphenyltin inhibits aromatase activity in
488 the human granulosa-like tumor cell line KGN. *Biochem Biophys Res Commun.* 289, 198-204.

489

490 Takahashi, S., Mukai, H., Tanabe, S., Sakayama, K., Miyazaki, T., Masuno, H., 1999. Butyltin
491 residues in livers of humans and wild terrestrial mammals and in plastic products. *Environ Pollut.*
492 106, 213-218.

493

494 Tanaka T, Narazaki M, Kishimoto T. 2014. IL-6 in inflammation, immunity, and disease.
495 *Cold Spring Harb Perspect Biol.* 6(10):a016295.

496

497 Tsukazaki, M., Satsu, H., Mori, A., Sugita-Konishi, Y., Shimizu, M., 2004. Effects of tributyltin on
498 barrier functions in human intestinal Caco-2 cells. *Biochem Biophys Res Commun.* 315, 991-997.

499

500 Tu, J., Hu, Z., Chen, Z., 2013. Endothelial gene expression and molecular changes in response to
501 radiosurgery in in vitro and in vivo models of cerebral arteriovenous malformations. *Biomed Res*
502 *Int.* doi: 10.1155/2013/408253. Epub 2013 Oct 2.

503

504 Vilahur, G., Padro, T., Badimon, L., 2011. Atherosclerosis and thrombosis: insights from large
505 animal models. *J Biomed Biotechnol.* 2011:907575. doi: 10.1155/2011/907575. Epub 2011 Jan 2.
506 Review..

507

508 Whalen, M.M., Loganathan, B.G., Kannan, K., 1999. Immunotoxicity of environmentally relevant
509 concentrations of butyltins on human natural killer cells in vitro. *Environ Res.* 81, 108-116.

510

511 Wiseman, S., Marlborough F., Doubal, F., Webb, D.J., Wardlaw, J., 2014. Blood markers of
512 coagulation, fibrinolysis, endothelial dysfunction and inflammation in lacunar stroke versus non-
513 lacunar stroke and non-stroke: systematic review and meta-analysis. *Cerebrovasc Dis.* 37, 64–75.

514

515 Yamada, J., Inoue, K., Furukawa, T., Fukuda, A., 2010. Low-concentration tributyltin perturbs
516 inhibitory synaptogenesis and induces neuronal death in immature but not mature neurons. *Toxicol*
517 *Lett.* 198, 282-288.

518

519 Yamada, T., Egashira, N., Imuta, M., Bando, A., Takahisa, Y., Saito, M., Oishi, R., 2011.
520 Comparison of injuring effects of vesicant, irritant, and nonvesicant anticancer drugs on endothelial
521 cells. *J Pharmacol Sci.* 117, 125-128.

522

523 Yoshizuka, M., Hara, K., Doi, Y., Mori, N., Yokoyama, M., Ono, E., Fujimoto, S., 1992. The toxic
524 effects of bis (tributyltin) oxide on the rat thoracic aorta. *Histol Histopathol.* 7, 445-449.

525

526 Zannoni, A., Giunti, M., Bernardini, C., Gentilini, F., Zaniboni, A., Bacci, M.L., Forni, M., 2012.
527 Procalcitonin gene expression after LPS stimulation in the porcine animal model. *Res Vet Sci* 93,
528 921-927.

529

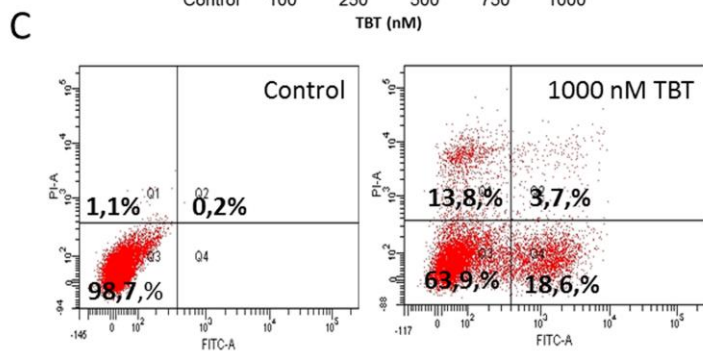
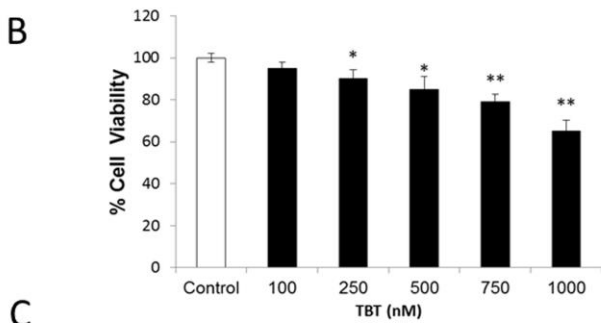
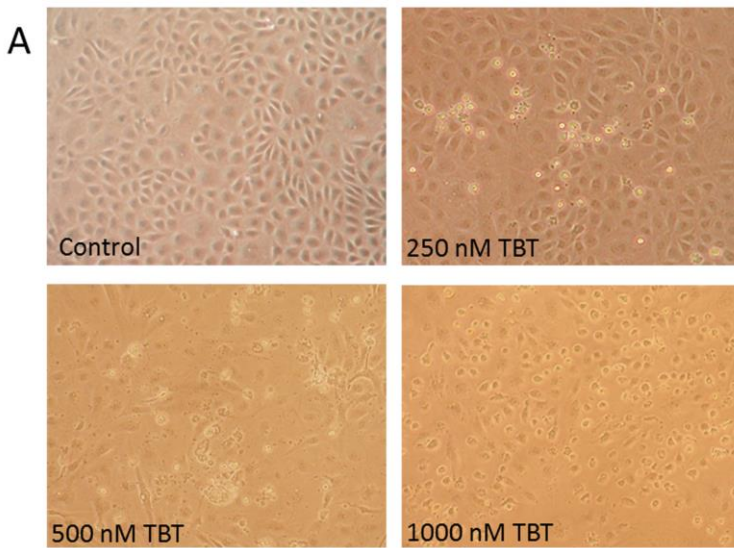
530 Zaragoza, C., Gomez-Guerrero, C., Martin-Ventura, J.L., Blanco-Colio, L., Lavin, B., Mallavia, B.,
531 Tarin, C., Mas, S., Ortiz, A., Egido, J., 2011. Animal models of cardiovascular diseases. *J Biomed*
532 *Biotechnol.* 2011:497841. doi: 10.1155/2011/497841. Epub 2011 Feb 16. Review.

533

534 Zhang J., Zuo, Z., Zhu, W., Sun, P., Wang, C., 2013. Sex-different effects of tributyltin on brain
535 aromatase, estrogen receptor and retinoid X receptor gene expression in rockfish (*Sebasticus*
536 *marmoratus*). *Mar Environ Res.* 90, 113-118.

537

538 Figure 1. A) Representative images of pAECs morphology under standard culture conditions or in
 539 the presence of increasing TBT doses; cultures exposed to TBT demonstrated a higher number of
 540 detached cells. Effect of TBT on cell viability. B) Cytotoxicity assessed by LDH release assay on
 541 pAECs exposed to increasing TBT concentrations. Data represents mean \pm S.E. of four
 542 independent experiments ****P < 0.01**. C) Annexin V / PI binding assay, representative cytograms
 543 showing control (left) and pAECs exposed to TBT 1000 nM (right). TBT treatment induced both
 544 apoptotic and necrotic cells.

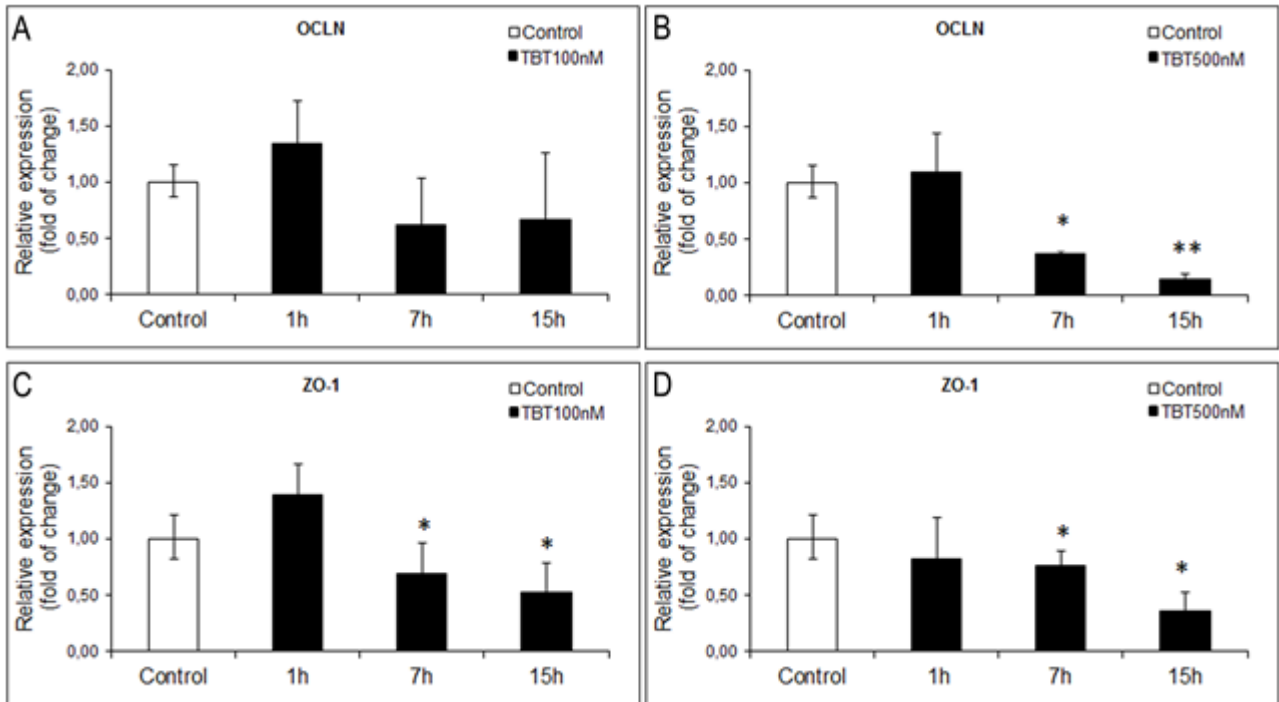


545

546 Figure 2. Relative gene expression of tight junction: OCLN (A,B) and ZO-1(C,D) in pAECs treated
547 with TBT (100 and 500 nM) at different period (1, 7 and 15 hours). Relative expression was
548 calculated as fold of change in respect to the control cells ($2^{-\Delta\Delta Ct}$ method). Error bar represents the
549 range of relative expression.

550 **P < 0.01 and *P < 0.05 when compared to control.

551 Occludin (OCLN); Zonula Occludens-1 (ZO-1)

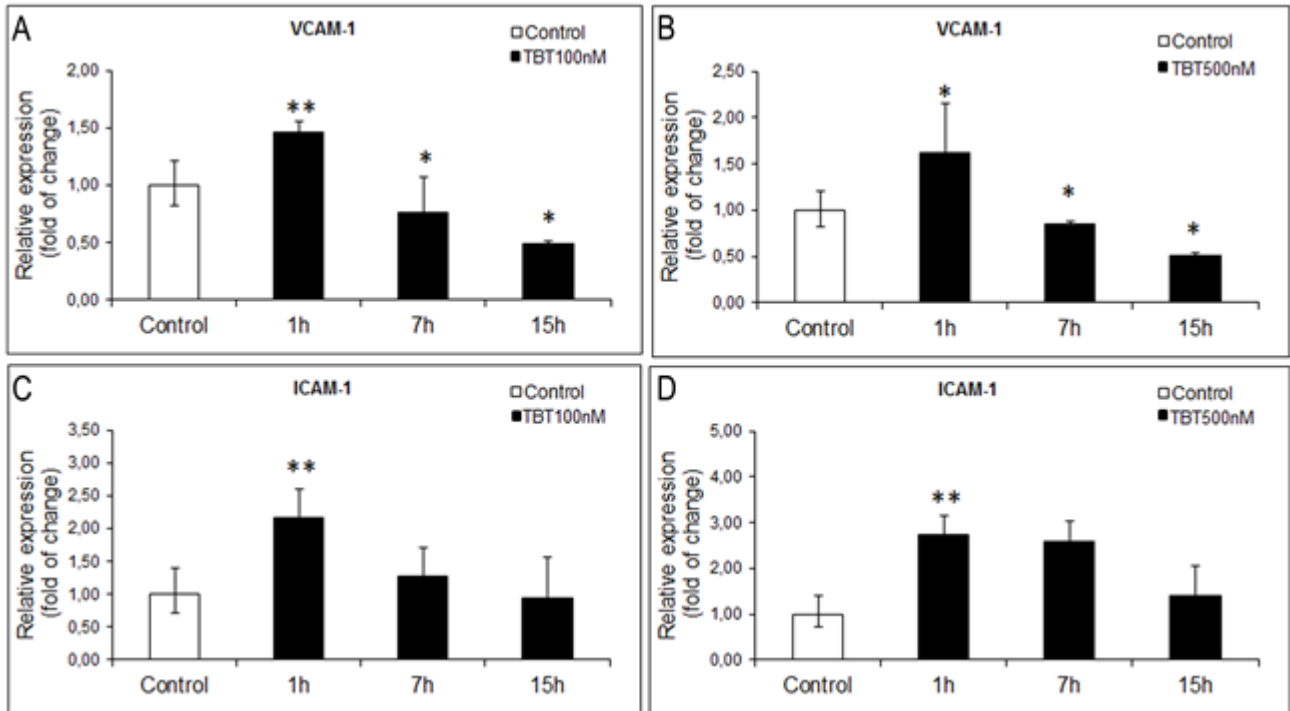


552

553 Figure 3. Effect of TBT exposure on expression levels of genes related to adhesion
554 molecules:VCAM-1 (A,B), ICAM-1 (C,D) in pAECs treated with TBT (100 and 500 nM) at different
555 period (1, 7 and 15 hours). Relative expression was calculated as fold of change in respect to the
556 control cells ($2^{-\Delta\Delta Ct}$ method). Error bar represents the range of relative expression.

557 **P < 0.01 and *P < 0.05

558 Intercellular Adhesion Molecule-1 (ICAM-1); Vascular Cell Adhesion Molecule-1 (VCAM-1)

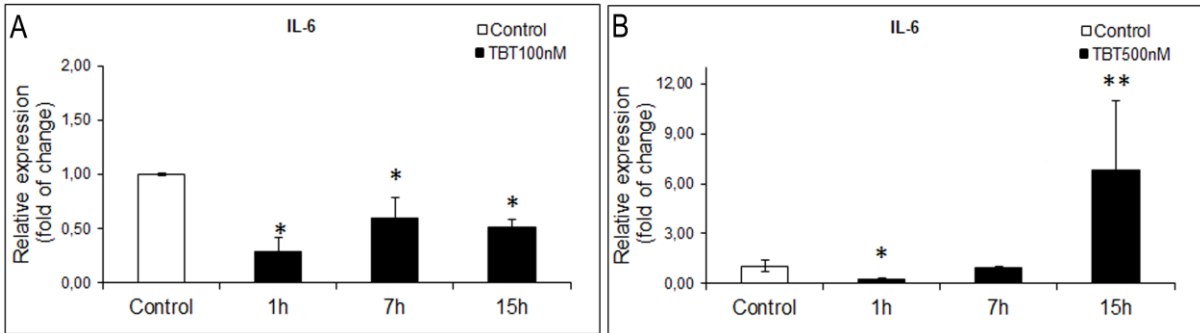


559

560 Figure 4. Effect of TBT exposure on expression levels of IL-6 gene in pAECs. treated with TBT 100
561 nM (A) and 500 nM (B) at different period (1, 7 and 15 hours). Relative expression was calculated
562 as fold of change in respect to the control cells ($2^{-\Delta\Delta Ct}$ method). Error bar represents the range of
563 relative expression.

564 **P < 0.01 and *P < 0.05

565 Interleukin 6 (IL-6)

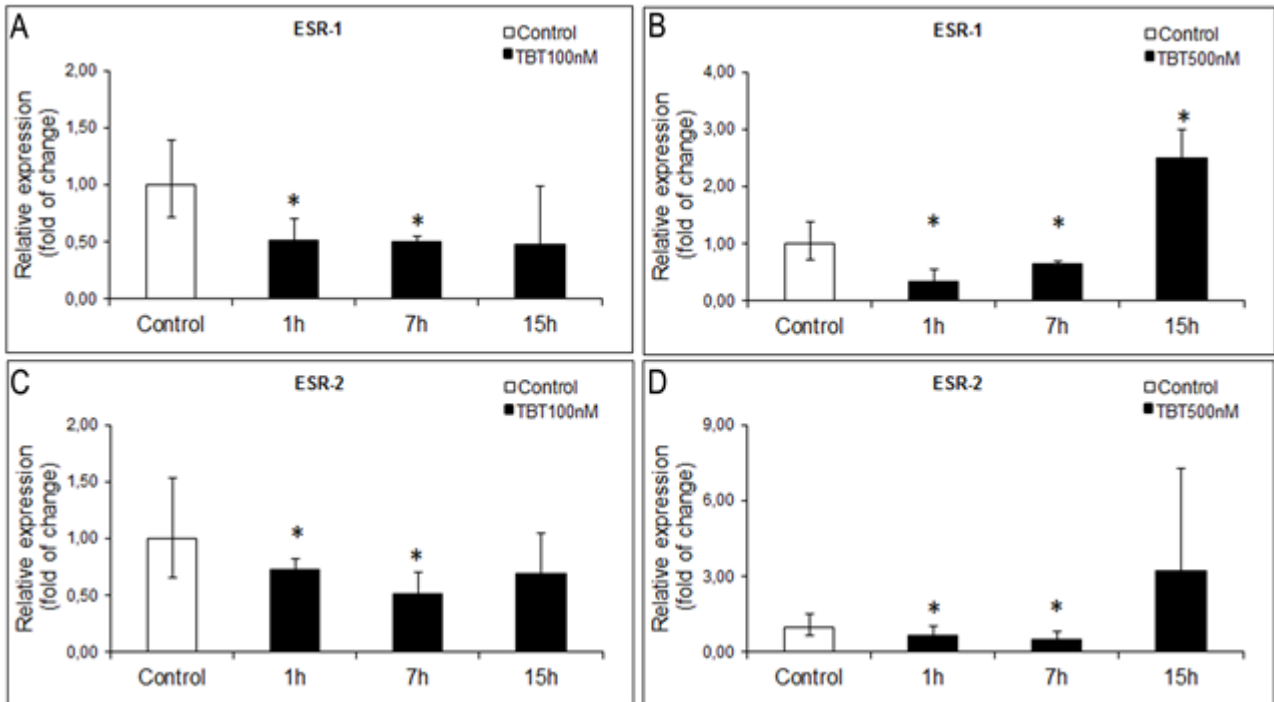


566

567 Figure 5 Effect of TBT exposure on expression levels of ESR-1 and ESR-2 genes in pAECs
568 treated with TBT (100 and 500 nM) at different period (1, 7 and 15 hours). Relative expression was
569 calculated as fold of change in respect to the control cells ($2^{-\Delta\Delta Ct}$ method). Error bar represents the
570 range of relative expression.

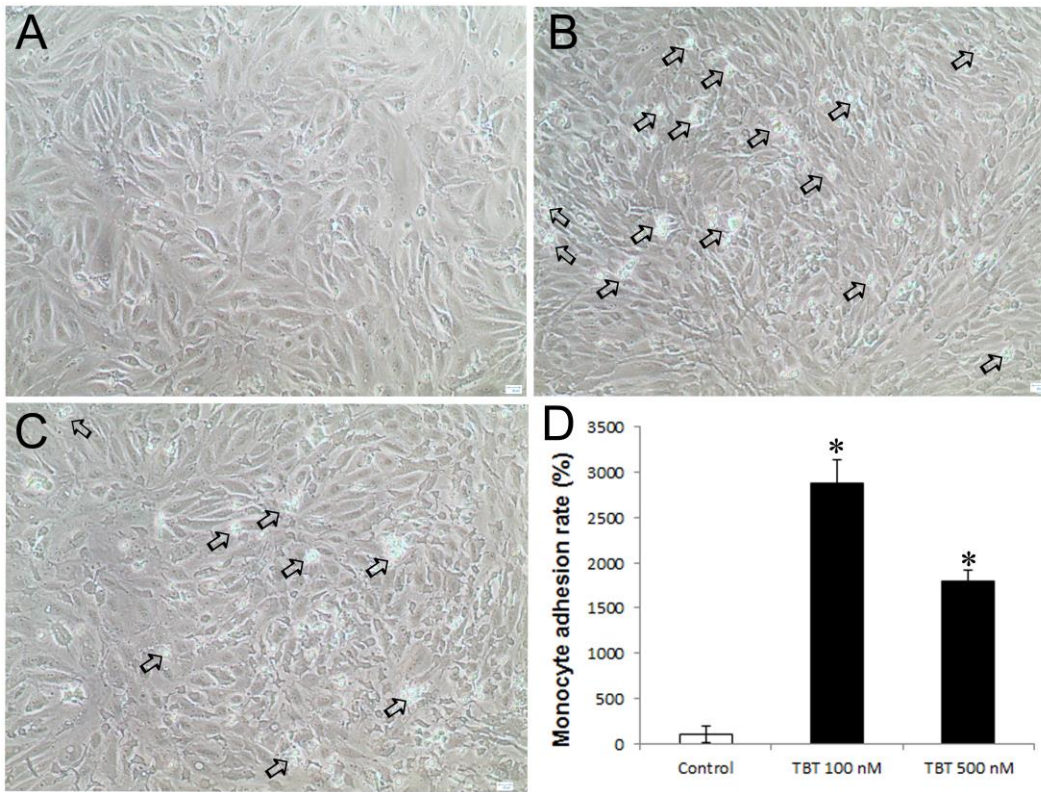
571 *P< 0.05

572 estrogen receptor 1 (ESR-1); estrogen receptor (ESR-2)



573

574 Figure 6 Effect of TBT on monocyte adhesion. A) pAECs in standard culture condition (control); B,
575 C) pAECs treated with TBT 100nM or 500 respectively (10X). The arrows indicated adhered
576 monocytes. D) Bars represent the mean Monocyte adhesion rate represented as the percentage
577 compared with control group. *P< 0,01



578

579 Table 1: Sequences, expected PCR product lengths, and accession numbers in the NCBI
 580 database of the swine primers for indicated genes.

Gene	Sequence (5'-3')	Length (bp)	Acc. No.
Estrogen receptor 1 (ESR-1)	For: CGGAGAGGAGGGAGAATGTTG	142 bp	NM214220
	Rev: GGCTGTTCTTCTTAGTGTTTAAAT		
Estrogen receptor 2 (ESR-2)	For: AACCTTAACTCTCCTGTCTCCTAC	250 bp	NM001001533
	Rev: GCTGGCAATGGATGGCTAAAG		
Occludin (OCLN)	For: ATCAACAAAGGCAACTCT	157 bp	NM001163647.2
	Rev: GCAGCAGCCATGTACTCT		
Zonula Occludens-1 (ZO-1)	For: AGTGCCGCCTCCTGAGTTTG	147 bp	AJ318101
	Rev: CCATCCTCATCTTCATCATCTTCTACAG		
Vascular cell adhesion molecule (VCAM-1)	For: GAGGATGGAAGATTCTGGAATTTACG	172 bp	NM213891
	Rev: ATCACTAGAGCAGGTCATGTTTAC		
Intercellular adhesion molecule (ICAM-1)	For: GCCACTAACAATCACGCATAATG	212 bp	NM213816
	Rev: TGCTCACTGTAGTCCCTTCTG		
Interleukin-6 (IL-6)	For: CTGGCAGAAAACAACCTGAACC	94 bp	NM214399.1
	Rev: TGATTCTCATCAAGCAGGTCTCC		
β -Actina (Act)	For: ATCGTGCGGACATCAAGGA	169 bp	AJ312193
	Rev: AGGAAGGAGGGCTGGAAGAG		
GAPDH	For: TGGTGAAGGTCGGAGTGAAC	120 bp	AF017079
	Rev: TGTAGTGGAGGTCAATGAAGGG		
HPRT	For: GGACAGGACTGAACGGCTTG	115 bp	AF143818
	Rev: GTAATCCAGCAGGTCAGCAAAG		

581