

Application of the EROD-H4IIE bioassay for the determination of dioxins in pork in comparison to high resolution gas chromatography coupled to high resolution mass spectrometry[#]

Aplicación del bioensayo EROD-H4IIE para la determinación de dioxinas en carnes de cerdo en comparación con la cromatografía de gases de alta resolución acoplada a espectrometría de masas de alta resolución

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RESUMEN

El bioensayo EROD-H4IIE se utiliza en la detección de hidrocarburos halogenados planares, presentando ventajas sobre la química analítica, como velocidad, simplicidad, precisión, alta sensibilidad y bajo costo, siendo un valioso bioensayo para estudios de biomonitorio. Se ha aplicado exitosamente como método de cribado para la detección de dioxinas y furanos (PCDD/Fs) en carne de pollos broiler. En el presente trabajo realizamos un estudio para detectar PCDD/Fs en carne de cerdo, aplicando el bioensayo y la cromatografía de gases acoplada a espectrometría de masas de alta resolución (HRGC/HRMS). Se tomaron 59 muestras compuestas de lomo vetado de cerdo en la planta faenadora de 6 plantales de Chile, durante el beneficio de animales entre 2004 y 2007 y una muestra fue tomada en 2011. Las concentraciones promedio de PCDD/Fs obtenidas mediante HRGC/HRMS oscilaron entre 0,22 y 0,34 pg WHO-TEQ/g de grasa. El contenido máximo fue 0,71 pg/g de grasa. El mayor valor promedio de los congéneres fue 0,1 pg/g de grasa de 2,3,4,7,8-PeCDF (entre 0,03 y 0,28 pg/g de grasa). Por tanto, las muestras no excedieron los límites máximos permitidos por la legislación nacional e internacional. Comparando ambos métodos, de las 59 muestras el bioensayo sobrestimó 36 resultados, subestimó 19 y 4 fueron similares. 15 muestras excedieron 1 pg TCDD-EQ/g de tejido y 5 superaron los 2 pg TCDD-EQ/g de tejido. No se estableció una equivalencia entre EROD-H4IIE y HRGC/HRMS para la detección de PCDD/Fs en carne de cerdo, no existiendo asociación significativa entre las variables ($r = -0,142$, $P \geq 0,2840$).

Palabras clave: dioxinas, EROD/H4IIE, HRGC/HRMS, carne de cerdo.

SUMMARY

The EROD-H4IIE cell bioassay is a screening method for the detection of planar halogenated hydrocarbons (PHH), it has several advantages over analytical chemistry like speed, simplicity, accuracy, high sensitivity and low cost which makes it a valuable bioassay for biomonitoring studies. It has been successfully used as screening method for the detection of dioxins and furans (PCDD/Fs) in meat from broiler chicken. The aim of this study was to detect PCDD/Fs in pork, by using both the bioassay and the high resolution gas chromatography/high resolution mass spectrometry (HRGC/HRMS). 59 composite samples of pork chuck loin were taken at a slaughtering plant of 6 Chilean production facilities between 2004 and 2007, with one sample being taken in 2011. Mean concentrations of PCDD/Fs obtained by HRGC/HRMS ranged between 0.22 and 0.34 pg WHO-TEQ/g fat. The maximum was 0.71 pg WHO-TEQ/g fat. The average value of the congeners was 0.1 pg WHO-TEQ fat-2,3,4,7,8-PeCDF (between 0.03 and 0.28 pg/g fat). Therefore, the samples did not exceed the maximum allowed by national and international legislation. When comparing the results obtained with the two methods, 36 out of 59 sample results were overestimated by the bioassay, while 19 were underestimated and 4 were similar. 15 samples exceeded 1 pg/g TCDD-EQ tissue and only 5 exceeded 2 pg TCDD-EQ/g tissue. It was not possible to establish an equivalence between EROD-H4IIE and HRGC/HRMS for the detection of PCDD/Fs in pork since there was not a significant association between variables ($r = -0.142$, $P \geq 0.2840$).

Key words: dioxins, EROD/H4IIE, HRGC/HRMS, pork.

INTRODUCTION

Dioxins (polychlorinated dibenzo-*p*-dioxins, PCDDs and dibenzofurans, PCDFs) are unwanted contaminants almost principally produced by industrial processes, in-

cluding incineration (Olie 1980, USEPA 2001), pyrolysis processes, chlorine bleaching of paper and pulp, and the manufacture of some pesticides, herbicides, and fungicides (Gilpin *et al* 2003). Dioxins did not exist prior to industrialization except in very small amounts due to natural combustion and geological processes (Czuczwa *et al* 1984, Ferrario and Byrne 2000). From a total of 7,270 samples collected in the period 1999-2008 from 19 Member States of European Union, PCDD/Fs congeners

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comprised between 30% and 74% of the total concentration depending on food or feed group, while mono-ortho PCBs comprised between 15% and 45% of dioxin-like PCBs (EFSA 2010). According to USEPA, between 1987 and 2000, there was approximately a 90% reduction in the release of PCDD/Fs and PCBs to the circulating environment of the United States from all known sources combined. This reduction in environmental releases of dioxin-like compounds is caused by source-specific regulations, improvements in source technology, advancements in the pollution control technologies and the end of the chlorinated phenol business in large sectors of the chemical industry (USEPA 2006, Hites 2011). In addition, the relative proportions of dioxin congeners emitted to the environment have changed so that greater proportions of dioxin congeners of lower toxicity are emitted. This pattern of decline has resulted in significant reductions in average human exposure to 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD), the dioxin congener of greatest toxicity and concern, and current exposures to dioxin are typically composed of smaller amounts of lower toxicity congeners (Hays and Aylward 2001, Petreas *et al* 2001, Hites 2011). However, the presence of dioxins has been reported in pork for human consumption (Bernard *et al* 2002, Guruge *et al* 2005, Hoffman *et al* 2006, Hoogenboom *et al* 2007, Covaci *et al* 2008, Kim *et al* 2011, PoultryMed¹), raising concerns due to accumulation of these xenobiotics in the food chain, particularly in animal fat. In this sense, the European Union has adopted a series of regulatory measures to reduce the presence of PCDD/Fs, in addition to monitoring food of animal origin, including pork from the Community member states, by using high resolution gas chromatography/high resolution mass spectrometry (HRGC/HRMS). This analytical technique requires investment in infrastructure and equipment at a considerable cost as well as highly trained technicians to detect individual congeners of PCDD/Fs and DL PCBs (Valdovinos 2009, Babin *et al* 2010). Therefore, a number of screening assays has been developed, such as the 7-ethoxyresorufin-*O*-deethylase (EROD)-bioassay, the aryl hydrocarbon hydroxylase (AHH) bioassay, the enzyme immunoassay (EIA), the chemical-activated luciferase gene expression (CALUX), the gel retardation of AhR DNA binding (GRAB) assay, the recAhr DELFIA assay kit, the Ah receptor (AhR) (or filtration) assay with radio-labeled dioxins, the Ah-immunoassay (AhIA) (Behnisch *et al* 2001), the chemical-activated fluorescent expression (CAFLUX) (Zhao *et al* 2010) and DR-EcoScreen® bioassay (Anezaki *et al* 2009, Kojima *et al* 2010). A viable alternative is to use *in vitro* bioassay cell line H4IIE rat hepatoma as screening method in pork production, considering that Schoffer *et al* (2011) determined the

equivalence between the results of the bioassay of meat from broiler chickens with HRGC/HRMS, showing that the first one provides very accurate estimates ($R^2=0.885$), and is therefore considered a useful technique for biomonitoring, as a screening method, in broiler chicken production and can be extended to other animal production systems. Therefore, the objective of this study is to determine the presence of dioxins and furans in pork produced in Chile by HRGC/HRMS in pg WHO-TEQ/g fat and H4IIE-EROD bioassay in pg TCDD-EQ²/g of sampling tissue, and to determine the equivalence of the results generated by the bioassay as a screening method and HRGC/HRMS as identity confirmatory method.

MATERIAL AND METHODS

SAMPLES

59 composite samples of pork were used, each sample of 1 kg was obtained from chuck loins of 10 animals from the same origin, obtained from the slaughtering plant of 6 production facilities in Chile, coded as P1, P2, P3, P4, P5 and P6, for the slaughter of animals (180 days of age) between 2004 and 2007, with one sample being taken in 2011. Samples were ground-up using an industrial meat grinder in the slaughtering plant (BESTE® TK-12), obtaining two samples of 250 g for the EROD-H4IIE bioassay and 2 samples of 250 g for the HRGC/HRMS analysis (sample and countersample). They were placed in aluminum containers, sealed and frozen at -70° C in the laboratory to pending analysis.

The samples that were taken until 2007 came from export meat and the sample taken in 2011 came from meat for domestic consumption.

EXTRACTION AND PURIFICATION FOR APPLICATION OF H4IIE CELL BIOASSAY

The extraction process was performed according to the method described by Nicks and Tillitt (2003). A 20 g sample of meat was weighed and 60 g of sodium sulfate were added (Na_2SO_4) to dry the sample. Then each dried sample was homogenized in a blender (Osterizer® 4172). The fat extraction was performed in an automated Soxhlet (VELP® Scientifica SER 148) during 2 hours and 30 minutes, with a 1:1 mixture of dichloromethane-hexane. Determination of the lipid content of the extract was performed by gravimetric calculations. To clean the extract, the sample was first passed through a glass column filled with Na_2SO_4 , potassium silicate (KS), silica 60:40 (Grade 62 silica gel, 60-200 mesh, 150 Å, SIGMA-ALDRICH® mixed with H_2SO_4) with dichloromethane. Then the extract was again exposed to a second cleaning column con-

¹ <http://www.poultrymed.com/Poultry/Templates/showpage.asp?DBID=1&LNGID=1&TMID=178&FID=871&PID=0&IID=11684>
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² TCDD-EQs is used in this document to describe the toxic equivalents (TEQs)-derived from EROD-H4IIE bioassay.

taining Na₂SO₄, silica gel 60 (Grade 60 silica gel, 70-230 mesh, 0.063-0.200 mm; Merck®), KS and silica 60:40 with a mixture of dichloromethane: hexane/3:97. The obtained sample was reduced using a rotary evaporator (Heidolph® Laborota 4000) to a volume of 1 mL. The solvent was exchanged using gaseous nitrogen to obtain a final extract of 150 µL dissolved in isooctane. All the used solvents were HPLC grade.

EROD-H4IIE CELL BIOASSAY

EROD-H4IIE cell bioassay was applied for the detection of PCDDs, and DL-PCBs, according to the protocol described by Tillitt *et al* (1991) and modified by Nicks and Tillitt (2003). The hepatoma cell line *Rattus norvegicus* was used (ATCC®, code CRL-1548™), it was grown in an Eagle's basal medium modified by Dulbecco (D-MEM) enriched with 15% fetal bovine serum (FBS). Cells were maintained under standard conditions (37° C, 5% CO₂) and allowed to grow between 4 to 5 days, then they were seeded in microtiter plates Nunc® flat-bottom 96 well plate, in a volume of 300 µL/well with a density of 1.2 x 10⁴ cells/well. After 24 hours of growth the plate was dosed with the standard of 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD) in a set of 7 serial dilutions in a 1:2 ratio (50 pg/well to 0.069 pg/well) with three replicates of each (dilution 1:2). This standard was used to generate a dose-response curve according to which all samples were compared. The extracts of the samples and the quality control samples with 3 replicates each were dosed in a set of 7 in a 1:3 ratio. Similarly, dosed along with these samples were a positive control (PC) corresponding to tissue of *Cyprinus carpio* Linnaeus and a negative control or blank matrix (BM) of *Lepomis macrochirus* Rafinesque, reference materials of the Columbia Environmental Research Center, Missouri, USA. Furthermore, a procedure blank (PB) corresponding to a solution of dichloromethane-hexane 1:1 (HPLC grade) was used. After the dosage procedure, the cells were left under standard conditions for 72 hours before the reading, which was performed by removing the medium using a Thermo Weelwash® 4 Mk 2 plate washer, with ultrapure water, leaving approximately 60 µL of medium/well. After washing, the cells were incubated for 5 minutes, causing osmotic cytolysis, resulting in the exposure of cytochrome P-4501A1 (CYP1A1). Afterwards, the plate was removed from the incubator and 20 µL of buffer at 37° C with 80 µL of dicumarol were added. Subsequently, 20 µL of 5 µM of ethoxyresorufin and 20 µL of 5 µM NADPH were added. Finally, plates were placed in a fluorescence reader (Bio-Tek® FLx800™) that performs readings for 20 minutes with an excitation filter of 530 nm and an emission filter of 580 nm. This method allows reading of EROD activity, as well as the protein reading in the same well (Kennedy and Jones 1994). In the final stage of the assay, dose-response curves were used to determine the relative

potency of the extract (RPFs), comparing slopes values of the sample extracts with values of the standard TCDD slope to obtain toxic equivalents (TCDD-EQs) expressed in pg/g of sample (Mason *et al* 1985, Tillitt *et al* 1993, Whyte *et al* 2004). The recommendations of Whyte *et al* (2004) were considered for quality control of the bioassay, such as the use of a composite TCDD dose-response curve from the average of four independent determinations, the extraction in triplicate in at least the 5% of the analysed samples, the previously mentioned use of quality control samples (PC, MB and PB), and checking concentrations of resorufin, ethoxyresorufin, and NADPH reagents on each assay date using spectrophotometer.

HIGH RESOLUTION GAS CHROMATOGRAPHY COUPLED TO HIGH RESOLUTION MASS SPECTROMETRY

The analysis of 58 samples by HRGC/HRMS was performed by the Research and Productivity Council (RPC), New Brunswick, Canada. Two methods were used for this purpose: U.S. EPA Method 1613B, "Tetra-through Octa-Chlorinated Dioxins and Furans by Isotope Dilution HRGC/HRMS" and U.S. EPA Method 8290A, "Polychlorinated Dibenzodioxins (PCDDs) and Polychlorinated Dibenzofurans (PCDFs) by High-Resolution Gas Chromatography/High-Resolution Mass Spectrometry (HRGC/HRMS)", each with slight modifications (RPC Standard Operation Procedures DX09 and DX08). Dioxin-like PCBs (DL-PCBs) were not analysed in this study.

The sample (20 to 60 g) was enriched with a solution containing specified amounts of each of the 15 internal standards of isotopically labeled PCDD/Fs (Wellington Laboratories Inc., Guelph, Ontario, Canada). Soxhlet extraction was performed for 16 h with dichloromethane/hexane 1:1 (GC grade), then extracts were concentrated in a rotary evaporator (Buchi® RE 121 or Yamato® RE47). The fat content was determined by gravimetric analysis, the extracts were dissolved in hexane (GC grade). Afterwards a digestion was performed using silica 70:30 (silica gel 60. 100-200 particle size; Caledon® mixed with H₂SO₄). Then the extracts were cleaned up using a silica column of acidic/basic/silver nitrate (AgNO₃) and then using a second silica column with activated charcoal. When there was interference with chlorinated diphenyl ethers, sample extracts were cleaned up on a third basic alumina column. The final extract was enriched with a solution containing specified amounts of two isotopically labeled PCDD recovery standards (Wellington Laboratories Inc., Guelph, Ontario, Canada). A final volume of 20 micro µL was obtained. The HRGC/HRMS analysis was performed with a Hewlett Packard® HP 5890 series II gas chromatograph, coupled with VG Autospec high resolution®, mass spectrometer, resolution >10³, with selected multi-group ion monitoring; 1 µL injection volume; gas chromatography column Rtx-Dioxin2 60 m x 0.25 mm x 0.25 µm (Restek). Quantifica-

tion was performed using internal standards and the results were corrected for recoveries of internal standards.

The sample taken in 2011 was analysed in the Laboratory of Veterinary Pharmacology, Faculty of Veterinary Science of the Universidad de Chile (FARMAVET), applying similar analytical methods based on the USEPA protocols mentioned above. RPC's Analytical Services laboratories hold accreditation with the Standards Council of Canada (SCC) and conform to the requirements of ISO/IEC 17025. FARMAVET is accredited ISO 17025 by Instituto Nacional de Normalización (INN), which is responsible of the accreditation in Chile. Both laboratories used the toxicity equivalence factors (TEF) established by the World Health Organization (WHO), to calculate the total concentration of dioxin-like compounds expressed in toxic equivalents or WHO-TEQ (van den Berg *et al* 1998).

STATISTICAL ANALYSIS

The statistical software Minitab® version 15.0 for Windows (Minitab Inc., State College, PA, USA) was used. After obtaining the results expressed in pg WHO-TEQ/g fat for HRGC/HRMS and TCDD-EQs pg/g of tissue for EROD-H4IIE, a descriptive analysis of the data was performed for a subsequent correlation and regression analysis.

RESULTS

RESULTS OF HRGC/HRMS ANALYSIS

Table 1 shows the descriptive statistics of the results of sample analysis by HRGC/HRMS, which had low concentrations of PCDD/Fs and did not exceed the maximum allowed by Chilean legislation and the Republic of Korea of 2 pg WHO-TEQ/g fat (Minsalud 2008, Kim *et al* 2011) and the maximum allowed by the European of 1 pg WHO-TEQ/g fat (EC 2006). The average of these concentrations ranged from 0.22 pg/g fat (P5) and 0.34 pg/g fat (P2). The maximum content of dioxins amounting to 0.71 pg/g fat was observed in a sample of P2, however, this value did not exceed the maximum levels.

Regarding the congeners, when they were not detected by chromatographic analysis, the corresponding cal-

ulation in WHO-TEQ was performed using the *upper bound* concept, which considers the limit quantification for the contribution of each non quantified congener (EC 2012). Table 2 presents the mean concentrations of congeners in pg WHO-TEQ/g fat, with the highest average value 0.1 pg/g of 2,3,4,7,8-PeCDF (range between 0.03 and 0.28 pg/g fat) in P2 samples. The second highest average concentration corresponded to 1,2,3,7,8-PeCDD (one of the most toxic congener) with 0.091 pg/g fat (range between 0.05 and 0.14 pg/g fat). OCDD and OCDF (the less toxic congeners) presented the highest average concentrations in P1 with 0.00014 and 0.00226 pg/g fat respectively. Finally, no sample exceeded the action level concentration for pork (0.75 pg/g fat) established as a European Commission Recommendation, as part of an overall strategy to reduce the presence of PCDD/Fs and PCBs in the environment, feed and foodstuffs (EC 2011).

COMPARISON OF HRGC/HRMS AND H4IIE-EROD RESULTS

Table 3 shows an overestimation of the average results obtained by H4IIE/EROD bioassay compared to those obtained by HRGC/HRMS, however, when comparing the results of the 59 bioassay samples, 36 results were overestimated, 19 were underestimated and only four were similar. Figure 1 shows that both overestimations as underestimations of results were reported in samples from all production facilities. The highest bioassay overestimates were obtained with 3.25 pg TCDD-EQ/g of tissue compared to 0.21 pg WHO-TEQ/g of fat and 3.13 pg TCDD-EQ/g tissue compared to 0.20 pg WHO-TEQ/g of fat. On other hand, 15 samples exceeded 1 pg TCDD-EQ/g of tissue and only 5 exceeded 2 pg TCDD-EQ/g tissue. The highest bioassay underestimation was 0.08 pg TCDD-EQ/g tissue, compared to 0.52 pg WHO-TEQ/g fat measured with HRGC/HRMS.

Finally, the correlation analysis of the results obtained by both methods, indicates no significant association between variables ($r = -0.142$, $P \geq 0.2840$), therefore it was not possible to establish equivalence between HRGC/HRMS and EROD-H4IIE for the detection of dioxins in pork (figure 2).

Table 1. Descriptive statistics: HRGC/HRMS dataset in pg WHO-TEQ/g of fat.
Estadísticas descriptivas: Datos de HRGC/HRMS en pg WHO-TEQ/g de grasa.

Production Facility	n	Mean	SD	Min	P25	P50	P75	Max	CV(%)	CI 95%
1	8	0.24	0.06	0.17	0.19	0.23	0.28	0.33	21.73	0.18 - 0.28
2	11	0.34	0.18	0.18	0.20	0.27	0.55	0.71	52.94	0.21 - 0.46
3	8	0.32	0.11	0.19	0.26	0.27	0.40	0.52	34.37	0.23 - 0.41
4	7	0.27	0.07	0.21	0.21	0.23	0.37	0.38	25.92	0.20 - 0.34
5	7	0.22	0.09	0.12	0.15	0.21	0.34	0.35	40.90	0.14 - 0.31
6	18	0.23	0.10	0.07	0.15	0.21	0.29	0.48	43.47	0.17 - 0.28

Table 2. Average of dioxin and furan congeners in pg WHO-TEQ/g of fat in samples of pork from each production facility (P). The minimum and maximum values are shown between parentheses.

Promedios de congéneres de dioxinas y furanos en pg WHO-TEQ/g de grasa en las muestras de carne de cerdo de cada plantel (P). Los valores mínimos y máximos se muestran entre paréntesis.

PCDD/F	P1	P2	P3	P4	P5	P6
2,3,7,8-TCDD	0.044 (0.010-0.070)	0.065 (0.030-0.090)	0.067 (0.040-0.090)	0.042 (0.05-0.09)	0.049 (0.01-0.11)	0.051 (0.01-0.13)
1,2,3,7,8-PeCDD	0.048 (0.001-0.080)	0.08 (0.030-0.170)	0.091 (0.050-0.140)	0.071 (0.05-0.11)	0.081 (0.03-0.23)	0.073 (0.01-0.18)
1,2,3,4,7,8-HxCDD	0.005 (0.001-0.007)	0.008 (0.002-0.017)	0.007 (0.004-0.014)	0.006 (0.004-0.015)	0.031 (0.004-0.19)	0.005 (0.001-0.009)
1,2,3,6,7,8-HxCDD	0.005 (0.001-0.007)	0.007 (0.003-0.015)	0.008 (0.004-0.016)	0.006 (0.004-0.015)	0.006 (0.003-0.009)	0.005 (0.001-0.013)
1,2,3,7,8,9-HxCDD	0.005 (0.001-0.007)	0.005 (0.002-0.009)	0.008 (0.004-0.016)	0.007 (0.004-0.016)	0.006 (0.004-0.011)	0.006 (0.001-0.012)
1,2,3,4,6,7,8-HpCDD	0.005 (0.002-0.010)	0.002 (0.001-0.004)	0.003 (0.002-0.006)	0.004 (0.0024-0.0073)	0.003 (0.0017-0.004)	0.003 (0.001-0.0048)
OCDD	0.00014 (0.00007-0.00090)	0.00008 (0.00003-0.10500)	0.00012 (0.00006-0.00020)	0.00013 (0.00008-0.00020)	0.00007 (0.00005-0.00010)	0.0002 (0.00003-0.00028)
2,3,7,8-TCDF	0.026 (0.003-0.050)	0.031 (0.002-0.045)	0.031 (0.017-0.054)	0.028 (0.018-0.050)	0.021 (0.008-0.033)	0.027 (0.013-0.050)
1,2,3,7,8-PeCDF	0.003 (0.001-0.007)	0.003 (0.000-0.008)	0.005 (0.003-0.008)	0.003 (0.002-0.004)	0.003 (0.001-0.007)	0.003 (0.001-0.009)
2,3,4,7,8-PeCDF	0.034 (0.003-0.055)	0.1 (0.020-0.280)	0.064 (0.030-0.125)	0.064 (0.040-0.140)	0.031 (0.020-0.650)	0.036 (0.020-0.075)
1,2,3,4,7,8-HxCDF	0.007 (0.001-0.014)	0.014 (0.004-0.045)	0.011 (0.003-0.028)	0.01 (0.006-0.023)	0.006 (0.003-0.013)	0.005 (0.002-0.014)
1,2,3,6,7,8-HxCDF	0.005 (0.001-0.008)	0.011 (0.003-0.033)	0.007 (0.003-0.020)	0.007 (0.003-0.015)	0.003 (0.002-0.007)	0.004 (0.001-0.012)
2,3,4,6,7,8-HxCDF	0.004 (0.001-0.005)	0.007 (0.003-0.020)	0.007 (0.003-0.013)	0.006 (0.003-0.010)	0.003 (0.002-0.006)	0.005 (0.001-0.014)
1,2,3,7,8,9-HxCDF	0.005 (0.001-0.020)	0.007 (0.002-0.009)	0.01 (0.002-0.010)	0.006 (0.004-0.016)	0.004 (0.004-0.015)	0.007 (0.001-0.009)
1,2,3,4,6,7,8-HpCDF	0.003 (0.000-0.015)	0.002 (0.001-0.006)	0.002 (0.001-0.006)	0.002 (0.001-0.004)	0.001 (0.00-0.004)	0.001 (0.000-0.002)
1,2,3,4,7,8,9-HpCDF	0.0008 (0.0005-0.0020)	0.0005 (0.000-0.001)	0.001 (0.001-0.002)	0.0009 (0.000-0.003)	0.0007 (0.000-0.002)	0.0008 (0.000-0.002)
OCDF	0.00226 (0.0001-0.0180)	0.000009 (0.000-0.00003)	0.00002 (0.000-0.0001)	0.00002 (0.000-0.0001)	0.000009 (0.000-0.00002)	0.00001 (0.000-0.00004)

Table 3. Average results obtained by the EROD-H4IIE bioassay and by HRGC/HRMS.

Resultados promedio obtenidos por el bioensayo EROD-H4IIE y por HRGC/HRMS.

Production Facility	HRGC/HRMS (pg WHO-TEQ/g fat)		H4IIE (pg TCDD-EQ/g tissue)		n
	Mean	SD	Mean	SD	
P1	0.24	0.06	0.60	0.63	8
P2	0.34	0.18	0.79	0.78	11
P3	0.32	0.11	0.62	0.42	8
P4	0.27	0.07	0.39	0.40	7
P5	0.22	0.09	0.82	1.12	7
P6	0.23	0.11	1.01	0.96	18

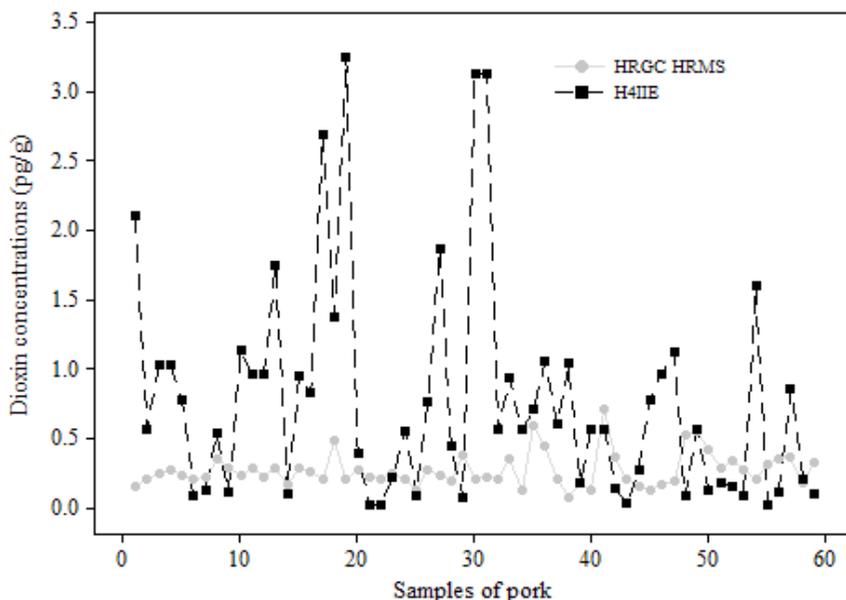


Figure 1. Comparison between results obtained by HRGC/HRMS in (pg WHO-TEQ/g fat) and H4IIE-EROD bioassay (TCDD-EQ pg/g tissue) in samples of pork.

Comparación entre resultados obtenidos mediante HRGC/HRMS (pg WHO-TEQ/g de grasa) y el bioensayo EROD-H4IIE (pg TCDD-EQ/g de tejido) en las muestras de carne de cerdo.

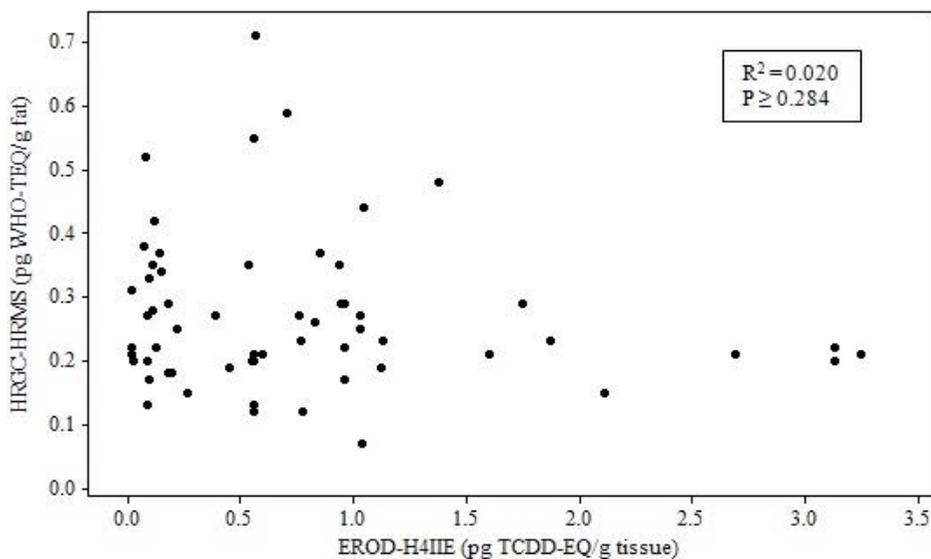


Figure 2. Correlation analysis between results obtained by EROD-H4IIE bioassay and HRGC-HRMS. There is no significant association between variables ($R^2 = 0.020$, $P \geq 0.284$).

Análisis de correlación entre los resultados obtenidos por el bioensayo EROD-H4IIE y mediante HRGC-HRMS. No hay asociación significativa entre las variables ($R^2 = 0,020$, $P \geq 0,284$).

DISCUSSION

Pork samples analysed by HRGC/HRMS, showed very low concentrations of PCDD/Fs and did not exceed the levels specified in domestic and foreign legislation (Minsalud 2008, EC 2006, Kim *et al* 2011). Only one sample was close to the intervention threshold for pork,

established as a recommendation by the European Union (EC 2006, 2011). These results differ substantially from those detected in Chilean pork exported to the Republic of Korea and Japan in 2008, whose concentrations ranged between 2.17 and 36.7 pg WHO-TEQ/g fat, concluding that these animals were fed zinc oxide contaminated with PCDD/Fs as a premix ingredient (Kim *et al* 2011). It is

therefore possible to infer that these contaminated pre-mixes were added to the diets of pigs after the year 2007 and the negative sample for 2011 would indicate that measures taken by the Chilean pork industry to prevent another case of contamination could be fulfilling their purpose.

The EROD-H4IIE bioassay for the detection of PCDD/Fs has proved to be very useful, since it is fast, reproducible, accurate, high sensitivity and lower cost than HRGC/HRMS (Denison *et al* 2004, Whyte *et al* 2004) and has been used successfully in fish and wildlife, among others (Whyte *et al* 2004). In this study the bioassay lasted an average of 12 days from the beginning of the extraction until the reporting of the results and it showed a high sensitivity (LOD = 0.142 ± 0.1208) and a high reproducibility considering the quality control criteria of the assay.

Schoffer *et al* (2011) demonstrated the equivalence between the bioassay and HRGC/HRMS for the detection of dioxins in broiler chicken meat, reporting that it can be a useful technique to biomonitor these xenobiotics in animal production. However, in this study it was not possible to estimate a significant equivalence between the results obtained from both methods in pork samples, because there was not significant correlation between the data produced by the two analytical methods, this precluded the use of a model to estimate the expected value of PCDD/Fs contamination, which would be obtained by HRGC/HRMS, only if the EROD-H4IIE bioassay is used. One of the problems identified is the overestimation of the values measured by the bioassay, regarding HRGC/HRMS. This observation was also reported by Hoogenboom *et al* (2007) who applied the DR CALUX[®] bioassay (using genetically modified H4IIE cells) to analyse 219 samples, mostly from pork fat, with 80 of them being identified as suspicious and showing a much higher response than the reference samples. These samples were analysed by HRGC/HRMS, effectively confirming 36 as positive. Overestimates have also been reported in the analysis of poultry samples (Schoffer *et al* 2011) and ash (Till *et al* 1997). The difference between the two methods may be due to compounds that can trigger the aryl hydrocarbon receptor (AhR) pathway, such as polycyclic aromatic hydrocarbons (Chaloupka *et al* 1993), polybrominated compounds (Baston and Denison 2011), indol-3-carbinol (13C), which is present in cruciferous plants and has been described as a moderate activity binder with the AhR receptor (Chen *et al* 1996), in addition to DL-PCBs which in this study work were not analysed by HRGC/HRMS. In this sense, it is necessary to include a method of extraction and separation of DL-PCBs from dioxins in the sample. On the other hand, the underestimation of results by H4IIE, which limits the bioassay, could be explained by the fact that some compounds that induce the EROD/CYP1A1 activity are also substrates for the enzyme CYP1A1, resulting in inhibition of response by competition that could result in an

underestimation of the total EROD activity obtained in complex samples (Denison *et al* 2004). An example of induction and inhibition has been described by Petrulis *et al* (2001) in samples contaminated with mixtures of halogenated aromatic compounds (HAC).

With regard to the positive samples detected by the EROD-H4IIE bioassay, considering the maximum limitation allowed under Chilean legislation (2 pg WHO-TEQ/g fat), only 5 samples (8.5% of the total number of samples) should have been confirmed by HRGC/HRMS; the number would have risen to 15 (25.4% of the total) if the European standard had been followed (1 pg WHO-TEQ/g fat), therefore, with either option and if applying monitoring to control the safety of meat with request of PCDD/Fs, the savings would have been substantial compared to the chromatographic analysis of the 59 samples.

Over 300 scientific studies have been published concerning the use of EROD-H4IIE bioassay, highlighting its characteristics of speed, simplicity and ability to integrate the effects of complex mixtures, allowing it to be a powerful analytical tool to be applied in risk assessments and biomonitoring of dioxins and DL-PCBs, but extreme care must be taken to generate reliable results (Whyte *et al* 2004). Since the results of this study indicate that the bioassay can be applied in pork for the detection of dioxins, further studies are needed to achieve equivalence between both methods, incorporating the removal of DL-PCBs and following the strict application of a program of quality control and quality assurance, including inter-laboratory calibration tests.

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REFERENCES

- Anezaki K, K Yamaguchi, S Takeuchi, M Iida, K Jin, H Kojima. 2009. Application of a bioassay using DR-EcoScreen cells to the determination of dioxins in ambient air: a comparative study with HRGC-HRMS analysis. *Environ Sci Technol* 43, 7478-7483.
- Babín M del M, P Sanz, MA Concejero, MA Martínez, JV Tarazona. 2010. *In vitro* cellular responses in the RTG-2 cell line to complex mixtures of dioxins and dioxin-like PCDDs, PCDFs and PCBs. *J Appl Toxicol* 30, 603-610.
- Baston DS, MS Denison. 2011. Considerations for potency equivalent calculations in the Ah receptor-based CALUX bioassay: Normalization of superinduction results for improved sample potency estimation. *Talanta* 83, 1415-1421.

- Behnisch PA, H Kazunori, S Schin-ichi. 2001. Bioanalytical screening methods for dioxins and dioxin-like compounds - a review of bioassay/biomarker technology. *Environ Int* 27, 413-439.
- Bernard A, F Broeckaert, G De Poorter, A De Cock, C Hermans, C Saegerman, G Houins. 2002. The Belgian PCB/dioxin incident: analysis of the food chain contamination and health risk evaluation. *Environ Research Section A* 88, 1-18.
- Chaloupka K, N Harper, V Krishnan, M Santostefano, LV Rodriguez, S Safe. 1993. Synergistic activity of polynuclear aromatic hydrocarbon mixtures as aryl hydrocarbon (Ah) receptor agonists. *Chem Biol Interact* 89, 141-158.
- Chen I, S Safe, L Bjeldanes. 1996. Indole-3-carbinol and diindolylmethane as aryl hydrocarbon (Ah) receptor agonists and antagonists in T47D human breast cancer cells. *Biochem Pharmacol* 51, 1069-1076.
- Covaci A, S Voorspoels, P Schepens, P Jorens, R Blust, H Neels. 2008. The Belgian PCB/dioxin crisis - 8 years later. An overview. *Environ Toxicol and Pharmacol* 25, 164-170.
- Czuczwa JM, BD Mc Veety, RA Hites. 1984. Polychlorinated dibenzo-p-dioxins and dibenzofurans in sediments from Siskiwit Lake, Isle Royale. *Science* 226, 568-569.
- Denison MS, B Zhao, DS Baston, GC Clark, H Murata, H Dalho. 2004. Recombinant cell bioassay for the detection and relative quantification of halogenated dioxins and related chemicals. *Talanta* 63, 1123-1133.
- EC, European Commission. 2006. Commission Regulation (EC) N°1881/2006 of 19 December 2006 setting maximum levels for certain contaminants in foodstuffs. Official Journal of the European Union. L 364/5. 20.12.2006.
- EC, European Commission. 2011. Recommendations. Commission Recommendation of 23 August 2011 on the reduction of the presence of dioxins, furans and PCBs in feed and food. (2011/516/EU). Official Journal of the European Union. 24.8.2011. L 218/23.
- EC, European Commission. 2012. Commission Regulation (EC) N°252/2012 of 21 March 2012 laying down methods of sampling and analysis for the official control of levels of dioxins, dioxin-like PCBs and non-dioxin-like PCBs in certain foodstuffs and repealing Regulation (EC) N° 1883/2006. Official Journal of the European Union L 84/1. 23.03.2012.
- EFSA, European Food Safety Authority. 2010. Results of the monitoring of dioxin levels in food and feed. Scientific report of EFSA. *EFSA Journal* 8, 1385.
- Ferrario J, C Byrne. 2000. The concentration and distribution of 2,3,7,8-dibenzo-p-dioxins/-furans in chickens. *Chemosphere* 40, 221-224.
- Gilpin RK, DJ Wagel, JG Solch. 2003. Production, distribution and fate of polychlorinated dibenzo p dioxins, dibenzofurans, and related organohalogenes in the environment. In: Schecter A, Gasiewicz TA (eds). *Dioxins and Health*. Wiley-Interscience Hoboken, NJ, New Jersey, USA, Pp 89-136.
- Guruge KS, N Seike, N Yamanaka, S Miyazaki. 2005. Polychlorinated dibenzo-p-dioxins, -dibenzofurans, and biphenyls in domestic animal food stuff and their fat. *Chemosphere* 58, 883-889.
- Hays SM, LL Aylward. 2001. Temporal trends in body-burden suggest that dioxin exposure in the general population have declined significantly. *Organohal Comp* 52, 214-216.
- Hites RA. 2011. Dioxins: An overview and history. *Environ Sci Technol* 45, 16-20.
- Hoffman MK, J Huwe, C Deyrup, M Lorentzen, R Zaylskie, N Clinch, P Saunders, W Sutton. 2006. Statistically designed survey of polychlorinated dibenzo-p-dioxins, polychlorinated dibenzofurans and co-planar polychlorinated biphenyls in U.S. meat and poultry, 2002-2003: results, trends, and implications. *Environ Sci Technol* 40, 5340-5346.
- Hoogenboom LAP, JCH Van Eijkeren, MJ Zeilmaker, MJB Mengelers, R Herbes, J Immerzeel, WA Traag. 2007. A novel source for dioxins present in recycled fat from gelatin production. *Chemosphere* 68, 814-823.
- Kim M, DG Kim, SW Choi, P Guerrero, J Norambuena, GS Chung. 2011. Formation of polychlorinated dibenzo-p-dioxins/dibenzofurans (PCDD/Fs) from a refinery process for zinc oxide used in feed additives: a source of dioxin contamination in Chilean pork. *Chemosphere* 82, 1225-1229.
- Kojima H, S Takeuchi, T Nagai. 2010. Endocrine disrupting Potential of Pesticides via Nuclear Receptors and Aryl Hydrocarbon Receptor. *J Health Sci* 56, 374-386.
- Mason G, T Sawyer, B Keys, S Bandiera, M Romkes, J Piskorska-Pliszczynska, B Zmudzka, S Safe. 1985. Polychlorinated dibenzofurans (PCDFs): correlation between *in vivo* and *in vitro* structure-activity relationships. *Toxicology* 37, 1-12.
- MINSAL, Ministerio de Salud, Chile. 2008. Resolución Exenta N°499 de 16 de agosto de 2008, Santiago, Chile.
- Nicks DK, DE Tillitt. 2003. H4IIE bioassay-derived 2,3,7,8-tetrachlorodibenzo-p-dioxin equivalents (TCDD-EQ) in fish collected in 2000 from large estuaries along the western coast of the United States. USGS, Columbia Environmental Research Center, Biochemistry & Physiology Branch, Final laboratory report FY 2003 - 30 - 01, 2003.
- Olie K. 1980. Chlorodibenzo-p-dioxins and chlorodibenzofurans are trace components of fly ash and flue gas of some municipal incinerators in the Netherlands. *Chemosphere* 9, 501-522.
- Petreas M, J She, P Visita, J Winkler, M McKinney, FR Brown, J Dhaliwal, G Denison, M Mok. 2001. Trends in persistent contaminants in California biota. *Symposia papers presented before the Division of Environmental Chemistry*, American Chemical Society, San Diego, CA, USA.
- Petrulis JR, G Chen, S Benn, J La Marre, NJ Bunce. 2001. Application of the ethoxyresorufin-O-deethylase (EROD) assay to mixtures of halogenated aromatic compounds. *Environ Toxicol* 16, 177-184.
- Schoffer JT, C Bustos-López, P Sotomayor, CA Mattar, A González, C Robles, F Samsing, O Acevedo, CE Valdovinos. 2011. Aplicación del bioensayo EROD-H4IIE para la determinación de dioxinas en carnes de pollos broiler: Un estudio de equivalencia con la cromatografía de gases de alta resolución acoplada a espectrometría de masas de alta resolución. *Arch Med Vet* 43, 259-266.
- Till M, P Behnisch, H Hagenmaier, KW Bock, D Schrenk. 1997. Dioxin like components in incinerator fly ash: a comparison between chemical analysis data and results from a cell culture bioassay. *Environ Health Persp* 105,

- 1326-1332.
- Tillitt DE, JP Giesy, GT Ankley. 1991. Characterization of the H4IIE rat hepatoma cell bioassay as a tool for assessing toxic potency of planar halogenated hydrocarbons in environmental samples. *Environ Sci Technol* 25, 87-92.
- Tillitt DE, TJ Kubiak, GT Ankley, JP Giesy. 1993. Dioxin-like toxic potency in Forster's Tern eggs from Green Bay, Lake Michigan, North America. *Chemosphere* 26, 2079-2084.
- USEPA, United States Environmental Protection Agency. 2001. Database of sources of environmental release of dioxin like compounds in the United States, EPA/600/C-01/012.
- USEPA, United States Environmental Protection Agency. 2006. An Inventory of sources and environmental releases of dioxin-like compounds in the United States for the years 1987, 1995 and 2000. National Center for Environmental Assessment, Washington DC; EPA/600/P-03/002F.
- Valdovinos CE 2009. Dioxinas y furanos en Chile: Riesgos potenciales de contaminación en la producción avícola y porcina. *Monografía*, Programa de Doctorado en Ciencias Silvoagropecuarias y Veterinarias. Campus Sur, Universidad de Chile, Santiago, Chile, Pp 3-4.
- Van den Berg M, L Birnbaum, BTC Bosveld, B Brunström, B Cook, M Feeley, JP Giesy, A Hanberg, R Hasegawa, SW Kennedy, T Kubiak, JC Larsen, FS van Leeuwen, AK Dijien Liem, C Nolt, RE Peterson, L Poellinger, S Safe, D Schrenk, D Tillitt, M Tysklind, M Younes, F Waern, T Zacharewski. 1998. Toxic Equivalency Factors (TEFs) for PCBs, PCDDs, PCDFs for humans and wildlife. *Environ Health Persp* 106, 775-792.
- Whyte JJ, CJ Schmitt, DE Tillitt. 2004. The H4IIE cell bioassay as an indicator of dioxin-like chemicals in wildlife and the environment. *Crit Rev Toxicol* 34, 1-83.
- Zhao B, DS Baston, E Khan, C Sorrentino, MS Denison. 2010. Enhancing the response of CALUX and CAFLUX cell bioassays for quantitative detection of dioxin-like compounds. *Sci China Chem* 53, 1010-1016.

