Chemosphere 108 (2014) 183–189

Contents lists available at ScienceDirect

Chemosphere

journal homepage: www.elsevier.com/locate/chemosphere

Probabilistic meta-analysis of risk from the exposure to Hg in artisanal gold mining communities in Colombia

Eduardo De Miguel *, Diana Clavijo, Marcelo F. Ortega, Amaia Gómez

Environmental Geochemistry Research and Engineering Laboratory, Universidad Politécnica de Madrid, Alenza 4, E-28003 Madrid, Spain

HIGHLIGHTS

- Data of Hg in air and in fish across Colombia are evaluated in terms of risk.
- Probability distribution functions are fitted to exposure and concentration data.
- Inhalation of Hg contributes more to the overall risk than ingestion of fish.
- The risk for the residents of mining communities greatly exceeds the threshold of 1.
- The risk for miner-smelters is 200 times higher than what is deemed acceptable.

ARTICLE INFO

Article history:
Received 12 October 2013
Received in revised form 6 December 2013
Accepted 5 January 2014
Available online 15 February 2014

Keywords:
Mercury
Artisanal gold mining
Colombia
Risk assessment
Health

ABSTRACT

Colombia is one of the largest per capita mercury polluters in the world as a consequence of its artisanal gold mining activities. The severity of this problem in terms of potential health effects was evaluated by means of a probabilistic risk assessment carried out in the twelve departments (or provinces) in Colombia with the largest gold production. The two exposure pathways included in the risk assessment were inhalation of elemental Hg vapors and ingestion of fish contaminated with methyl mercury. Exposure parameters for the adult population (especially rates of fish consumption) were obtained from nation-wide surveys and concentrations of Hg in air and of methyl-mercury in fish were gathered from previous scientific studies. Fish consumption varied between departments and ranged from 0 to 0.3 kg d^{-1}. Average concentrations of total mercury in fish (70 data) ranged from 0.026 to 3.3 μg g^{-1}. A total of 550 individual measurements of Hg in workshop air (ranging from <DL to 1 mg m^{-3}) and 261 measurements of Hg in outdoor air (ranging from <DL to 0.652 mg m^{-3}) were used to generate the probability distributions used as concentration terms in the calculation of risk. All but two of the distributions of Hazard Quotients (HQ) associated with ingestion of Hg-contaminated fish for the twelve regions evaluated presented median values higher than the threshold value of 1 and the 95th percentiles ranged from 4 to 90. In the case of exposure to Hg vapors, minimum values of HQ for the general population exceeded 1 in all the towns included in this study, and the HQs for miner-smelters burning the amalgam is two orders of magnitude higher, reaching values of 200 for the 95th percentile. Even acknowledging the conservative assumptions included in the risk assessment and the uncertainties associated with it, its results clearly reveal the exorbitant levels of risk endured not only by miner-smelters but also by the general population of artisanal gold mining communities in Colombia.

1. Introduction

According to the UN Industrial Development Organization (UNIDO, 2011), Hg amalgamation from artisanal small-scale gold mining (ASGM) results in the release of an estimated 1000 tons of Hg per year, constituting about 30% of the world's anthropogenic Hg emissions. The same report classifies Colombia as one of the largest per capita Hg polluters as a consequence of its artisanal gold mining operations, which have been steadily increasing following the rising price of this metal (Marrugo-Negrete et al., 2008). Compared to gravimetric separation methods, the concentration of gold using Hg amalgams presents several advantages: the process is less time-consuming and minimizes gold losses, and Hg is easily transported and inexpensive relative to the selling price of gold (Veiga et al., 2003). According to previous studies (Hincapie Montoya, 2006; Telmer and Veiga, 2008; Veiga, 2010;

---

* Corresponding author. Tel.: +34 91 336 6992; fax: +34 91 336 6948.
E-mail address: eduardo.demiguel@upm.es (E. De Miguel).

http://dx.doi.org/10.1016/j.chemosphere.2014.01.035
0045-6535/© 2014 Elsevier Ltd. All rights reserved.

Cordy et al., 2011), the annual Hg emissions/releases from ASGM in Colombia are approximately 75 tons for a gold output of 35 tons.

Very often, Hg amalgamation is carried out on site by unprotected workers. During this operation a large amount of Hg is accidentally or intentionally discharged to the environment and eventually reaches nearby fresh water bodies where, together with the significant amounts of mercury supplied by wet atmospheric deposition (Hammerschmidt and Fitzgerald, 2006), it is subjected to methylation and subsequently bioaccumulates in aquatic fauna (Ullrich et al., 2001; UNEP, 2013). In order to recover the gold, the amalgam is heated in open charcoal furnaces either on site, or in small workshops (or even in the home of the miner) and the emitted Hg vapors are inhaled by the unprotected artisanal miner-smelters, but also outdoors and at home by residents of the mining communities.

The geochemistry of Hg has been extensively investigated (Ullrich et al., 2001; Kocman et al., 2011) and its global biogeochemical cycle is well characterized. The impact of Hg environmental contamination on human health has also attracted much scientific attention, originally directed to large-scale industrial releases or agricultural applications (Gochfeld, 2003; Kobal et al., 2004, 2008). In the last couple of decades, the potential health problems associated with the use of Hg in gold mining have also been acknowledged and thoroughly investigated, particularly in South American countries with a significant gold production (Veiga and Meech, 1995; Akagi and Naganumab, 2000; Fadini and Jardim, 2001; Marrugo-Negrete et al., 2008; Molina et al., 2010; Velásquez-López et al., 2010; Medina Mosquera et al., 2011; Santos-Francés et al., 2011).

All this research activity is obviously motivated by the well-established chronic toxicity of Hg. According to the USEPA's IRIS database (USEPA, 2011), there is strong evidence of neurobehavioral toxicity (tremors, slower and attenuated brain activity, memory disturbance, sleep disorders) of low-level, long-term exposure to Hg vapor, as revealed by the human occupational inhalation studies of Fawer et al. (1983), Kobal et al. (2004, 2008), Liang et al. (1993), Ngim et al. (1992), Piikivi (1989), and Piikivi and Hanninen (1989). Methyl-mercury (MeHg) is also a highly toxic substance. Dietary ingestion of MeHg can result in developmental neuropsychological and neurofunctional impairment (Bose-O'Reilly et al., 2008, 2010; Grandjean et al., 1997; Budtz-Jørgensen et al., 1999; Mergler, 2002; Gochfeld, 2003). Mother-to-fetus transfer of MeHg has been reported to potentially cause cerebral palsy, mental retardation, and delayed walking and speech (Rice, 1995).

Given the elevated exposure of miners and residents in artisanal mining communities to Hg vapor and MeHg accumulated in fish, the aim of this study is to quantitatively assess the risk for these individuals from the exposure to both substances, and to demonstrate the usefulness of probabilistic risk assessments as a tool to categorize environmental problems on a nation-wide scale and to prioritize political and remedial actions.

2. Methodology

Following the standard model of human health risk assessment for non-cancer endpoints, the potential risk for miners and residents was quantified in terms of hazard quotients (HQs) defined as the ratio between the estimated level of exposure of the receptor and the estimate of the safe chronic exposure dose (or concentration, depending on the exposure route). An HQ larger than 1 would indicate an unacceptable level of systemic risk. The conceptual model for this risk assessment considers two main exposure pathways: Inhalation of Hg vapor arising from the burning of the amalgam, in workshops as well as outside and inside residences; and ingestion of MeHg-contaminated fish:

$$HQ_{inhalation} = \frac{EC}{RfC} \tag{1}$$

$$HQ_{ingestion} = \frac{I}{RfD} = \frac{C_{MeHg} \times IR_{fish} \times EF \times ED/(BW \times AT)}{RfD} \tag{2}$$

where EC – exposure concentration (mg m^{-3}); EF – exposure frequency (d year^{-1}); RfC – reference concentration (mg m^{-3}); ED – exposure duration (years); RfD – oral reference dose (mg kg^{-1} d^{-1}); BW – body weight (kg); C_{MeHg} – concentration of MeHg in fish (mg kg^{-1}); AT – averaging time (days); IR_{fish} – fish ingestion rate (kg d^{-1}).

Quantitative toxicity values for both Hg species were obtained from the USEPA's IRIS database, which assigns an Inhalation RfC of 0.0003 mg m^{-3} to elemental Hg, and an Oral RfD of 0.0001 mg kg^{-1} d^{-1} to MeHg. Bioaccessibility of MeHg in the gastro-intestinal tract and of elemental Hg in the respiratory tract was conservatively considered to be 100% based on current scientific consensus (Gochfeld, 2003), although an absorption factor of 0.95 for ingested MeHg was used by the USEPA in the Mercury Study Report to Congress and to arrive at its current RfD (USEPA, 2013). The assessment of risk from fish ingestion was carried out independently for each of the 12 Colombian departments (or provinces) where gold artisanal mining is most intense: Antioquia, Santander, Nariño, Cauca, Caldas, Guainía, Vaupés, Quindío, Bolívar, Chocó, Córdoba and Tolima. The risk associated with the inhalation of Hg vapor was evaluated with data from three mining towns in the department of Antioquia.

2.1. Population-related variables

Given the insufficient data available on children exposure variables, the assessment was restricted to the adult population. The information on fish consumption (IR_{fish}) was obtained from the studies of Perucho Gómez (2007) and Olivero (2002) and is given as ranges for each department. Table 1 presents these data together with the main local fish species in the diet of the communities included in the study (Agudelo, 1991; GTZ/Corponariño/P-Consult., 1992; Gómez and Martínez, 1993; Gómez et al., 1995; Ruiz et al., 1996; Lully, 1998; Olivero and Solano, 1998; Ramos et al., 2000; Cala, 2001; Idrovo et al., 2001; Olivero et al., 2001; FAO, 2002; Olivero and Johnson, 2002; Aguilera, 2004; Mosquera-Lozano et al., 2005; UPME, 2005; Hincapie Montoya, 2006; Mancera-Rodríguez and Álvarez-León, 2006; Marrugo et al., 2007; IMC, 2008; Navarro et al., 2008; Perea et al., 2008).

From the results of an informal local survey, residents (and miners) were considered to leave the mining community for two weeks per year, i.e. EF = 350 d year^{-1}. For inhalation of Hg vapor, the average worker was estimated to spend 8 h d^{-1} and 6 d week^{-1} (for a total of 300 d year^{-1}) exposed to the workshop atmosphere, and the remaining time to outdoor air and residential indoor air (assumed conservatively to have the same Hg concentration as outdoor air). Lastly, the average body weight of exposed individuals was assumed to be 72 kg for men and 59 kg for women, based on data from Aristizabal et al. (2007).

Table 1
Fish ingestion rates (kg d^{-1}) and main species of fish in the diet of residents in the twelve departments with the largest artisanal gold production in Colombia.

Departament	Average fish consumption (kg d^{-1})	Main fish species
Antioquia	0–0.050	Bocachico (*Prochilodus reticulatus magdalenae*), Doncella (*Ageneiosus pardalis*), carachaza (*Pseudorinelepis genibarbis*), Mojarrita (Hemigrammus ocellifer), Tilapia (*Oreochromis* sp.), Nicuro (*Pimelodus blochii – clarias*)
Santander		Bagre (*Mystus tengara*), Corvina (*Argyrosomus regius*), pez gato (*Pseudoplatystoma fasciatum*), Sabaleta (*Brycon henni*), Nicuro (*Pimelodus blochii – clarias*)
Nariño		Corvina (*Argyrosomus regius*), pez gato (*Pseudoplatystoma fasciatum*), Carpa (*Cyprinus carpio*), Trucha (*Oncorhynchus mykiss*)
Cauca	0.050–0.150	Bocachico (*Prochilodus reticulatus magdalenae*), Doncella (*Ageneiosus pardalis*), Arenca (*Triportheus magdalenae*), Corvina (*Argyrosomus regius*), Bagre (*Pseudoplatystoma fasciatum*), Nicuro (*Pimelodus blochii – clarias*)
Caldas		Bagre (*Pseudoplatystoma fasciatum*), Bocachico (*Prochilodus reticulatus magdalenae*), Nicuro (*Pimelodus blochii – clarias*), Sabaleta (*Brycon henni*), Tilapia (*Oreochromis* spp.)
Guainía		Bocachico (*Prochilodus reticulatus magdalenae*), Bagre (*Pseudoplatystoma fasciatum*), Mojarra amarilla (*Caquetaia kraussii*), Doncella (*Ageneiosus pardalis*)
Vaupés		Mojarra amarilla (*Caquetaia kraussii*), Bagre (*Pseudoplatystoma fasciatum*), arenca (*Triportheus magdalenae*), Mohino (*Leporinus muyscorum*)
Quindío		Bagre (*Pseudoplatystoma fasciatum*), mojarra amarilla (*Caquetaia kraussii*), Bocachico (*Prochilodus reticulatus magdalenae*).
Bolívar	0.150–0.300	Doncella (*Ageneiosus pardalis*), Bocachico (*Prochilodus reticulatus magdalenae*), Vizcaína (*Curimatus mivartii*), Arenca (*Triportheus magdalenae*), Acara azul (*Aequidens pulcher*), Mojarra amarilla (*Caquetaia kraussii*), Corvina (*Argyrosomus regius*), Picuda (*Salminus affinis*)
Chocó		Arenca (*Triportheus magdalenae*), Doncella (*Ageneiosus pardalis*), Bocachico (*Prochilodus reticulatus magdalenae*), Cuabina, Bagre (*Pseudoplatystoma fasciatum*), Corvina (*Argyrosomus regius*), Picuda (*Salminus affinis*)
Córdoba		Bocachico (*Prochilodus reticulatus magdalenae*), Doncella (*Ageneiosus pardalis*), Mojarra (*Petenia krauussii*), Corvina (*Argyrosomus regius*), Capaz (*Pimelodus grospkopfii*), Moncholo (*Hoplias malabaricus*)
Tolima		Bocachico (*Prochilodus reticulatus magdalenae*), Bagre (*Pseudoplatystoma fasciatum*), Mojarra amarilla (*Caquetaia kraussii*), Corvina (*Argyrosomus regius*), Capaz (*Pimelodus grospkopfii*), Moncholo (*Hoplias malabaricus*), Jacho (*Gephagus daemon*)

Table 2
Summary statistics of the distribution of average concentrations of Hg in fish ($\mu g\ g^{-}$).

	n	Min.	Median	Mean	p95	Max.	Std. dev.
Antioquia	7	0.450	0.750	1.364	3.270	3.300	1.297
Santander	4	0.050	0.190	0.533	1.478	1.700	0.782
Nariño	4	0.026	0.243	0.335	0.761	0.830	0.361
Cauca	4	0.160	0.295	0.313	0.479	0.500	0.150
Caldas	4	0.030	0.260	0.338	0.740	0.800	0.346
Guainía	2	0.170	0.300	0.300	0.417	0.430	0.184
Vaupés	2	0.170	0.300	0.300	0.417	0.430	0.184
Quindío	4	0.200	0.365	0.358	0.490	0.500	0.134
Bolívar	13	0.001	0.300	0.718	2.698	2.920	0.973
Chocó	5	0.026	0.370	0.536	1.239	1.341	0.548
Córdoba	12	0.130	0.323	0.522	1.537	2.800	0.725
Tolima	9	0.050	0.120	0.287	1.124	1.780	0.561

2.2. Exposure media concentration

A total of 70 values of concentration of Hg in fish muscle (Table 2), ranging from 0.001 to 3.3 $\mu g\ g^{-1}$, were obtained from the same sources previously listed for Table 1. Concentrations of total Hg in fish tissue were obtained after an acid digestion and were analyzed by cold vapor atomic absorption and atomic fluorescence (WHO/UNEP, 1976).

The analytical protocols and analytical equipment employed are described in detail in Cala (2001), Marrugo et al. (2007), Olivero and Johnson (2002), Olivero et al. (2001) and Olivero and Solano (1998). The dataset of Hg concentrations in fish was unevenly distributed among the different provinces, some having only two data (Guainia, Vaupes), and others up to thirteen (Bolivar). The number of measurements of Hg in air was considerably higher: 550 inside workshops and 261 in outdoor air (Table 3). These values of Hg in air were taken from Cordy and Lins (2010), Hincapie Montoya (2006), Veiga (2010) and UNIDO's Global Mercury Project as supplied by Corporación Autónoma Regional del Centro de Antioquía (CORANTIOQUIA, 2010). Elemental Hg in air was measured with LUMEX RA 915 + portable cold vapor atomic absorption analyzers and Jerome 431X spectrometers (Cordy and Lins, 2010; Veiga, 2010).

The probability distribution function representing the level of exposure associated with the ingestion of Hg-contaminated fish was obtained as follows: Each of the 70 concentration values of Hg in fish was regarded as an independent estimate of the average Hg concentration in fish in the corresponding province (*p* estimates per province). The probability distribution of the exposure to Hg in fish for each province is then generated by re-sampling 100 000 times (with sample size 1) the sample of *p* average concentration values and multiplying this concentration by a fish consumption value randomly selected from a uniform distribution between the maximum and minimum values indicated in Table 1, and by the rest of the exposure parameters (EF, ED, BW^{-1} and AT^{-1}). This process is summarized in Eq. (3).

$$for\ (i\ in\ 1:100000)\left\{\begin{array}{c} C_f = sample(\bar{x}_p, size = 1) \\ CR = sample(uniform(min(cr), max(cr)), size = 1) \\ I[i] = \frac{C_f \times CR \times ET \times EF \times ED}{BW \times AT} \end{array}\right. \qquad (3)$$

Eq. (3): Generation of the probability distribution function of the dietary average chronic ingestion of MeHg.

For the inhalation pathway, the probability distribution function for the average chronic exposure concentration was generated by sampling with replacement the population of concentration data with a sample size, *n*, equal to the size of the data set (*n* = 550 for the workshop environment, *m* = 261 for the outdoor/indoor environment), calculating the arithmetic mean of those *n* values, and multiplying this average concentration by the exposure time, frequency and duration assigned to each exposure environment, in a 100 000-iteration loop. This process is summarized in Eq. (4).

$$for\ (i\ in\ 1:100000) \begin{cases} C_{wks} = mean\ (sample(x_n, size = n, replacement = TRUE) \\ C_{out} = mean\ (sample(x_m, size = m, replacement = TRUE) \\ EC[i] = \frac{C_{wks} \times ET_{wks} \times EF_{wks} \times ED_{wks} + C_{out} \times \left(\sum_{j=1}^{3} ET_j \times EF_j \times ED_j\right)}{AT} \end{cases} \quad (4)$$

Eq. (4): Generation of the probability distribution function of the average chronic inhalation dose of Hg for miner-smelters.

The programming of probabilistic risk models was carried using R (R Development Core Team, 2004).

3. Results and discussion

The unacceptable levels of risk arrived at in this study (see discussion below), although outstandingly high in absolute terms, are not surprising when the average concentration values of elemental Hg in air in Colombian mining communities are compared with international maximum recommended values: WHO's annual time-weighted average of 0.001 mg m^{-3} (WHO, 2000) and the American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit value of 0.025 mg m^{-3} (time-weighted average for a normal 8-h workday and a 40-h workweek, OSHA, 2013) are amply exceeded in the samples included in this study, with mean values ranging between 0.004 mg m^{-3} and 0.0076 mg m^{-3} for outdoor and residential indoor air, and between 0.034 mg m^{-3} and 0.148 mg m^{-3} for workshop atmospheres (Table 3).

The situation is different in the case of exposure to Hg in fish. The USEPÁs criterion for MeHg in fish tissue of 0.3 μg g^{-1} (USEPA, 2001) lies within the range of median concentrations (0.12–0.37 μg g^{-1}) found in this study (except for the province of Antioquia, with a median value of 0.75 μg g^{-1}). The problem in this case seems to be exacerbated by the high ingestion rates of local fish which can reach values up to 0.3 kg d^{-1}, almost 10 times higher than the 0.05 kg d^{-1} used by the USEPA (USEPA, 2004), although slightly lower than the consumption rates described for some fishing communities in the Brazilian Amazonia (Mergler, 2002; Sousa et al., 2008).

Fig. 1 presents graphically the distribution of HQs associated with the dietary intake of MeHg for the 12 provinces included in the study. The shape of these functions is strongly controlled by the distribution of average concentrations of MeHg in fish in each province. For the first 6 provinces in Fig. 1, there is a clear separation between a majority of tightly grouped, low concentration values and a few high ones, with a low p50/maximum ratio. When combined with the uniform distributions used to approximate ingestion rates, the resulting HQ functions present long right tails or in the case of Cordoba and Tolima, with the highest number of data, a bimodal distribution. As the asymmetry of the distributions of average concentrations of MeHg decreases (last 6 provinces in Fig. 1) the resulting HQ functions approximate log-normal or even normal distributions. For the inhalation exposure pathway, on the other hand, the probability functions representing the HQs of miner-smelters and residents follow a normal distribution in all three towns included in the study.

Tables 4 and 5 present a summary description of the resulting HQ distributions for the 12 departments (ingestion) and 3 towns (inhalation) included in this study. The simultaneous occurrence of elevated rates of local-fish consumption in these mining-fishing communities and the relatively high levels of MeHg in fish tissue result in HQ distributions for the ingestion pathway whose median values exceed the threshold level of 1 in 10 of the 12 provinces included in the study. All p95 values are higher than 1, and those for the provinces with the highest fish consumption rates range between HQ = 45 and HQ = 90. For women, with a lower body weight, the results are on average 22% higher than those presented in Table 4.

Exposure to Hg vapors in workshops where the amalgam is burnt results in HQ distributions for workers with shockingly high median values ranging from 43 to 168 and minimum values higher than 90 in two of the three towns investigated. The risk from inhalation for the general population is approximately one order of magnitude lower than for miner-smelters in two of the three towns investigated (and approximately half that HQ in the third), but the minimum HQ values are all higher than the threshold value of 1.

The contribution of ingestion of MeHg-contaminated fish to the aggregate risk is lower than that of inhalation of Hg vapor for residents, with differences between both exposure pathways within one order of magnitude. For miners-smelters exposed to Hg vapors during the burning of the amalgam, the contribution of inhalation is 2 orders of magnitude higher than that of fish ingestion. These results are in accordance with those of previous studies in similar exposure scenarios (Hacon et al., 1997).

The outcome of this risk assessment, however valid and alarming, needs to be interpreted with caution. One source of uncertainty arises from the lack of accompanying data on other trace elements like Se or Ca, which might attenuate the potential harm associated with exposure to Hg (Sakamoto et al., 1996; Yoneda and Suzuki, 1997; Osman et al., 1998; Vasconcellos et al., 2000). Also, for the fish intake pathway the sample of average concentrations is small, the mercury analyzed in the fish is total mercury (and the MeHg concentration could be as much as 10% lower), and a GI absorption rate of 100% for MeHg, was considered while a more prudent assumption used by USEPA is 95% (thus the fish-intake risk might be discounted by as much as 5%). Finally, at these high levels of exposure it is unlikely that the toxicity data published - and used in this study – for both species of Hg represent the real dose–response relationship. Therefore, the outcome from the risk assessment cannot be interpreted in strict quantitative terms.

Table 3
Summary statistics of the distribution of concentrations of inorganic Hg in outdoor air and workshops' atmospheres in mining towns of Antioquia (mg m^{-3}).

	Town	n	Min.	Median	Mean	p95	Max.	Std. dev.
Workshop atmosphere	Remedios	147	0.0050	0.1000	0.1476	0.4440	0.6520	0.1425
	Segovia	373	<DL	0.1290	0.1829	0.5382	0.9990	0.1861
	Bagre	30	0.0040	0.0175	0.0336	0.1619	0.1800	0.0475
Outdoor air	Remedios	94	<DL	0.0040	0.0040	0.0114	0.0160	0.0039
	Segovia	146	<DL	0.0040	0.0076	0.0193	0.1420	0.0187
	Bagre	21	0.0004	0.0060	0.0067	0.0110	0.0120	0.0033

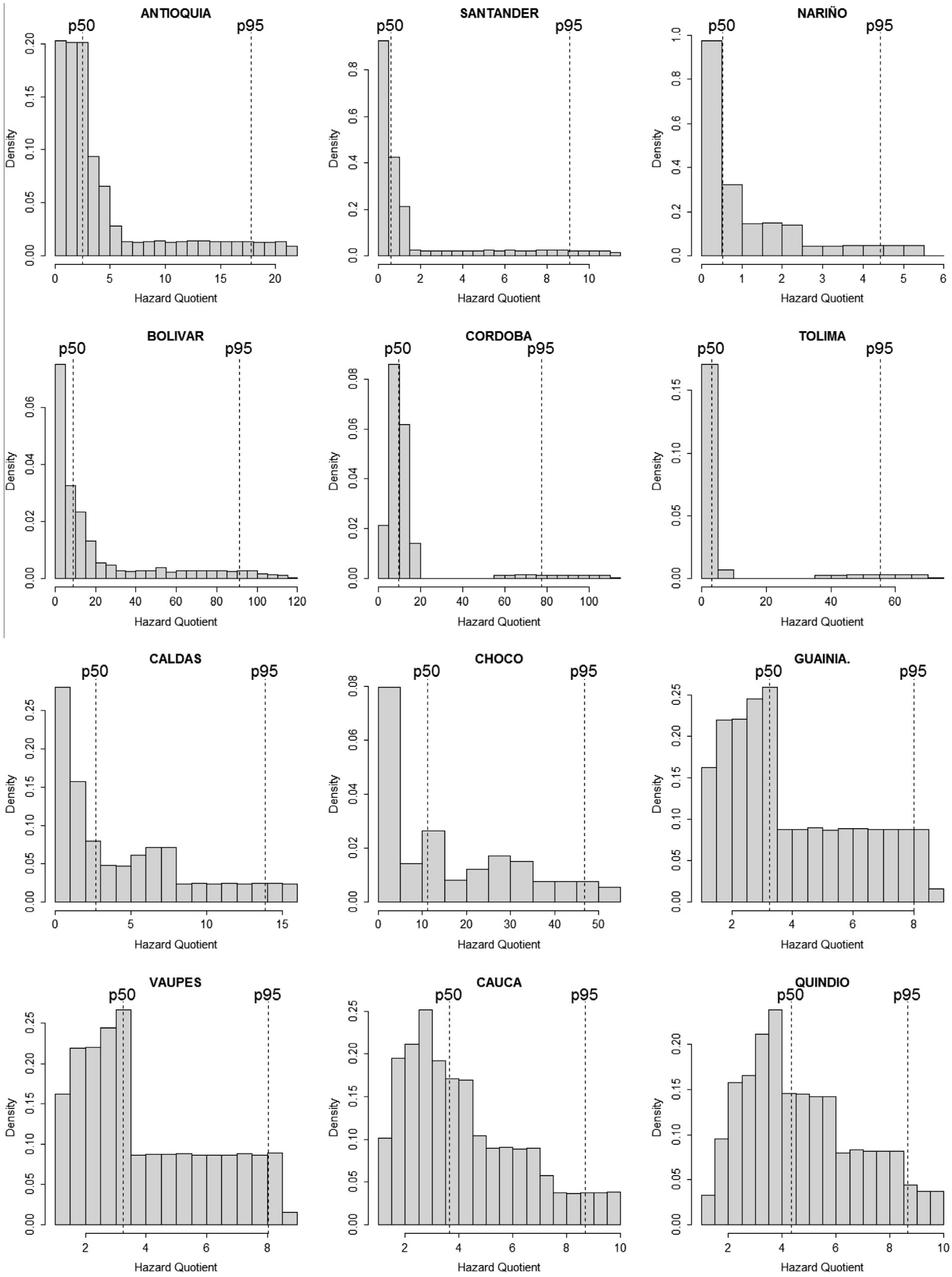

Fig. 1. HQ density functions for the fish-consumption exposure pathway for each of the 12 provinces included in the study. Density functions have been generated by re-sampling 100000 times the sample of average concentration values and a uniform distribution for fish consumption in each province, as detailed in Eq. (3).

Table 4
Summary statistics of the distribution of Hazard Quotients associated with the ingestion of Hg-contaminated fish.

	Min.	Median	Mean	p95	Max.	Std. dev.
Antioquia	2.1E−05	2.5	4.5	17.8	22.0	5.3
Santander	2.0E−06	0.6	1.8	9.1	11.3	2.8
Nariño	2.3E−07	0.5	1.1	4.4	5.5	1.4
Cauca	1.1	3.6	4.2	8.7	10.0	2.2
Caldas	0.2	2.7	4.5	13.9	16.0	4.4
Guainía	1.1	3.2	4.0	8.0	8.6	2.1
Vaupés	1.1	3.2	4.0	8.0	8.6	2.1
Quindío	1.3	4.3	4.8	8.7	10.0	2.1
Bolívar	0.0	8.8	21.5	91.2	116.7	28.8
Chocó	0.5	11.1	16.1	46.8	53.6	15.3
Córdoba	2.6	9.6	15.5	77.5	111.9	21.2
Tolima	1.0	3.3	8.6	55.4	71.1	16.3

Table 5
Summary statistics of the distribution of Hazard Quotients associated with the inhalation of Hg in outdoor air and workshops' atmospheres, in mining sites of Antioquia.

		Min.	Median	Mean	p95	Max	Std. dev.
Miner-smelters	Remedios	93.4	130.6	130.9	147.2	176.1	9.7
	Segovia	136.3	168.2	168.4	183.0	211.5	8.7
	Bagre	20.6	43.0	43.5	56.1	79.3	7.2
Residents	Remedios	7.7	12.8	12.9	15.0	18.7	1.3
	Segovia	9.7	24.0	24.4	33.0	55.0	4.9
	Bagre	12.0	21.4	21.4	25.0	30.1	2.2

4. Conclusions

Probabilistic risk assessment cannot substitute for thorough clinical studies for the purposes of public health control and intervention. However, given the cost and difficulty of sampling human populations, by using more readily accessible environmental data, risk assessment is indeed a useful tool to give quantitative meaning to problems of environmental and occupational exposure to pollutants, to categorize these problems, and most importantly, to prioritize remedial actions.

As an illustrative example of this potential, a probabilistic risk assessment in Colombia's artisanal gold mining communities has clearly highlighted the exorbitant levels of risk endured by residents of these communities. The fact that these mining communities are also fishing communities whose diet is based on the fish they catch in the local rivers exacerbates the problem as exposure from ingestion of Hg-contaminated fish is added to the inhalation of Hg-laden outdoor air. For miner-smelters who burn the amalgam in artisanal workshops the risk of developing adverse health effects is even higher, reaching levels 200 times higher than what is deemed acceptable in most environmental regulations and standards.

Whether these extraordinary levels of risk will result in adverse health effects cannot be directly inferred from a risk assessment that makes use of published Reference Doses and Concentrations derived from low dose-low response models. A follow up of this study including clinical data would allow establishing those quantitative relationships between elevated levels of exposure and long-term health effects.

Acknowledgments

The authors would like to express their gratitude to Prof. Michael Gochfeld for his extremely helpful review, which has increased the quality of the manuscript substantially.

References

Agudelo, A., 1991. Comparación de las respuestas bioeléctricas de grupos de dos y cuatro ejemplares de Carassius auratus, sometidos a tres concentraciones subletales de mercurio. Facultad de Ciencias, Universidad de Antioquía, Medellín (Antioquía).

Aguilera, M., 2004. La Mojana: riqueza natural y potencial económico. Documento sobre economía regional, No. 48. Cartagena de Indias: Banco de la República – Sucursal Cartagena.

Akagi, H., Naganumab, A., 2000. Human exposure to mercury and the accumulation of methylmercury that is associated with gold mining in the Amazon Basin, Brazil. J. Health Sci. 46 (5), 323–328.

Aristizabal, J., Restrepo, M., Estrada, A., 2007. Evaluación de la composición corporal de adultos sanos por antropometría e impedancia bioeléctrica. Biomédica 27, 216–224.

Bose-O'Reilly, S., Lettmeier, B., Matteucci Gothe, R., Beinhoff, C., Siebert, U., Drasch, G., 2008. Mercury as a serious health hazard for children in gold mining areas. Environ. Res. 107, 89–97.

Bose-O'Reilly, S., McCarty, K., Steckling, N., Lettmeier, B., 2010. Mercury Exposure and Children's Health. Curr. Probl. Pediatr. Adolesc. Heatlh Care 40, 186–215.

Budtz-Jørgensen, E., Keiding, N., Grandjean, P., 1999. Methylmercury neurotoxicity independent of PCB exposure. Environ. Health Perspect. 107, 236–237.

Cala, P., 2001. Occurrence of mercury in some commercial fish species from the Magdalena and Meta Rivers in Colombia. Dahlia. Rev. Aso. Col. Ictiol. 4, 15–19.

CORANTIOQUIA, 2010. Proyecto Mercurio Colombia. <http://proyectomercuriocolombia.com/mercurio/Antioquia.html>.

Cordy, P., Lins, N., 2010. Patterns of atmospheric mercury contamination in Colombia. Prepared for UNIDO – United Nations Industrial Development Organization.

Cordy, P., Veiga, M.M., Salih, I., Al-Saadi, S., Console, S., Garcia, O., Mesa, L.A., Velásquez-López, P., Roeser, M., 2011. Mercury contamination from artisanal gold mining in Antioquia, Colombia: the world's highest per capita mercury pollution. Sci. Total Environ., 154–160.

Fadini, P., Jardim, W., 2001. Is the Negro River Basin (Amazon) impacted by naturally occurring mercury? Sci. Total Environ. 275, 71–82.

FAO, 2002. Food and Agriculture Organization of the United Nations: Programa de desarrollo sostenible de la región de "La Mojana". Colombia: Departamento Nacional de Planeación, DNP y Organización de las Naciones Unidas para la Agricultura y la Alimentación, FAO.

Fawer, R.F., DeRibaupierre, U., Guillemin, M.P., Berode, M., Lobe, M., 1983. Measurement of hand tremor induced by industrial exposure to metallic mercury. J. Ind. Med. 40, 204–208.

Gochfeld, M., 2003. Cases of mercury exposure, bioavailability, and absorption. Ecotoxicol. Environ. Saf. 56, 174–179.

Gómez, Q., Martínez, R., 1993. Contenido de mercurio en varias especies de peces de agua dulce y harinas comerciales de pescado. Departamento de Farmacia, Facultad de Ciencias, Universidad Nacional de Colombia.

Gómez, Q., Martínez, R., Podlesky, E., 1995. Contenido de mercurio en varias especies de peces del río Magdalena y en harinas comerciales de pescado. Informe técnico mercurio: un contaminante ambiental ubicuo y peligroso para la salud humana. Biomédica 15(3), 183.

Grandjean, P., Weihe, P., White, R., 1997. Cognitive deficit in 7-year-old children with prenatal exposure to methylmercury. Neurotoxicol. Teratol. 20, 1–12.

GTZ/Corponariño/P-Consult., 1992. Mitigación de emisiones de mercurio en la pequeña minería aurífera de Nariño.

Hacon, S., Rochedo, E.R., Campos, R., Rosales, G., Lacerda, L.D., 1997. Risk assessment of mercury in Alta Floresta. Amazon Basin – Brazil. Water, Air Soil Pollut. 97, 91–105.

Hammerschmidt, C.R., Fitzgerald, W.F., 2006. Methylmercury in freshwater fish linked to atmospheric mercury deposition. Environ. Sci. Technol. 40, 7764–7770.

Hincapie Montoya, U., 2006. Diagnostico para la implementación de sistemas de gestión ambiental en el distrito minero Segovia-Remedios. Departamento de Antioquia, Secretaria de productividad y competitividad, Medellín.

Idrovo, A.J., Manotas, L.E., Villamil de García, G., Ortiz, O.E., Silva, E., Romero, S.A., 2001. Niveles de mercurio y percepción del riesgo en una población minera aurífera del Guainía (Orinoquia colombiana). Biomédica 21 (2), 134–141.

IMC, 2008. Información Minera de Colombia: Mercurio, el nudo en Remedios y Segovia. <http://www.imcportal.com/contenido.php?option=shownews&newsid=2687&render=page>.

Kobal, A.B., Horvat, M., Prezelj, M., Kobal, D., Sesek, B.A., Krsnik, M., Dizdarevic, T., Mazej, D., Falnoga, I., Stibilj, V., Arneric, N., Osredkar, J., 2004. The impact of long-term past exposure to elemental mercury on antioxidative capacity and lipid peroxidation in mercury miners. J. Trace Elem. Med. Biol. 17, 261–274.

Kobal, A.B., Prezelj, M., Horvat, M., Krsnik, M., Gibičar, D., Osredkar, J., 2008. Glutathione level after long-term occupational elemental mercury exposure. Environ. Res. 107, 115–123.

Kocman, D., Kanduc, T., Ogrinc, N., Horvat, M., 2011. Distribution and partitioning of mercury in a river catchment impacted by former mercury mining activity. Biogeochemistry 104, 183–201.

Liang, Y.-X., Sun, R.-K., Sun, Y., Chen, Z.-Q., Li, L.-H., 1993. Psychological effects of low exposure to mercury vapor: application of a computer-administered neurobehavioral evaluation system. Environ. Res. 60, 320–327.

Lully, A., 1998. Diagnóstico, base de producción limpia y programa de capacitación en la explotación aurífera. Convenio Especial de Cooperación para Programas de Competitividad y Desarrollo Tecnológico Productivo entre el Servicio Nacional de Aprendizaje SENA: La Cooperación para el Desarrollo Sostenible del Norte y Oriente Amazónico C.D.A. y la Secretaría Ejecutiva del Convenio Andrés Bello SECAB (Convenio 00051-97).

Mancera-Rodríguez, N., Álvarez-León, R., 2006. Estado del conocimiento de las concentraciones de mercurio y otros metales pesados en peces dulceacuícolas de colombia. Acta Biol. Colomb. 11 (1), 3–23.

Marrugo, J., Lans, E., Benítez, L., 2007. Hallazgo de mercurio en peces de la ciénaga de ayapel, Córdoba, Colombia. Rev. MVZ Córdoba 12 (1), 878–886.

Marrugo-Negrete, J., Benitez, L., Olivero-Verbel, J., 2008. Distribution of Mercury in several environmental compartments in an aquatic ecosystem impacted by gold mining in Northern Colombia. Arch. Environ. Contam. Toxicol. 55, 305–316.

Medina Mosquera, F.M., Ayala Mosquera, H.J., Perea, J.D., 2011. Determination of pollution in people involved in mercurial mining gold in the Mining District of San Juan, department of Chocó, Colombia. Bioetnia 8 (2), 195–206.

Mergler, D., 2002. Review of neurobehavioral deficits and river fish consumption from the Tapajo's (Brazil) and St. Lawrence (Canada). Environ. Toxicol. Pharmacol. 00, 1–7.

Molina, C., Gibon, F., Duprey, J., Dominguez, E., 2010. Transfer of mercury and methylmercury along macroinvertebrate food chains in a floodplain lake of the Beni River, Bolivian Amazonia. Sci. Total Environ. 408, 3382–3391.

Mosquera-Lozano, Y., Torres-Ibarguen, A., Lozano-Largacha, Y., Pereamena, B., 2005. Incidencia del mercurio por la explotación minera en algunas especies de peces en el río Condoto, Chocó-Colombia.

Navarro, A., Lans, E., Marrugo, J., 2008. Niveles totales de mercurio en peces del embalse de la hidroeléctrica de Urrá, Colombia (CA-089).

Ngim, C.H., Foo, S.C., Boey, K.W., Jeyaratnam, J., 1992. Chronic neurobehavioral effects of elemental mercury in dentists. Br. J. Ind. Med. 49, 782–790.

Olivero, J., 2002. UTF/COL/0024: Programa de desarrollo sostenible de la región de la Mojana, Colombia.

Olivero, J., Johnson, B., 2002. El lado gris de la minería del oro: la contaminación con mercurio en el norte de Colombia. Ed. Alpha.

Olivero, J., Solano, B., 1998. Mercury in environmental samples from a waterbody contaminated by gold mining in Colombia, South America. Sci. Total. Environ. 217, 83–89.

Olivero, J., Johnson, B., Mendoza, B., Olivero, R., 2001. Mercury Pollution in Colombia, CS-3. Abstract 6th Internal. Conference on Mercury as a Global Pollutant. Minamata, Japón.

OSHA, 2013. Occupational Safety and Health: Guideline for Mercury Vapor. <http://www.osha.gov/SLTC/healthguidelines/mercuryvapor/recognition.html>.

Osman, K., Schütz, A., Åkesson, B., Maciag, A., Vahter, M., 1998. Interactions Between Essential and Toxic Elements in Lead Exposed Children in Katowice, Poland. Clin. Biochem. 31 (8), 657–665.

Perea, A., Gómez, E., Mayorga, Y., Triana, C., 2008. Caracterización nutricional de pescados de producción y consumo regional en Bucaramanga, Colombia. ALAN 58 (1).

Perucho Gómez, E., 2007. PROYECTO TCP/RLA/3111: Mejoramiento de los mercados internos de productos pesqueros en America Latina y el Caribe.

Piikivi, L., 1989. Cardiovascular reflexes and low long-term exposure to mercury vapor. Int. Arch. Occup. Environ. Health 61, 391–395.

Piikivi, L., Hanninen, H., 1989. Subjective symptoms and psychological performance of chlorine-alkali workers. Scand. J. Work Environ. Health 15, 69–74.

R Development Core Team, 2004. R: A Language and Environment for Statistical Computing. <http://www.R-project.org>.

Ramos, C., Estévez, S., Giraldo, E., 2000. Nivel de contaminación por metilmercurio. Departamento de Ingeniería Civil y Ambiental, Centro de Investigaciones en Ingeniería Ambiental (CIIA), Universidad de Los Andes. Available online. <http://www.hruschka.com/hg-net/members/claudia/metilmercurio_en_la_mojana.doc>.

Rice, D., 1995. Neurotoxicity of lead, methylrmercury, and PCBs in relation to the Great Lakes. Environ. Health Perspect. 103 (suppl 9), 71–87.

Ruiz, J., Fandiño, C., Romero, G., Guevara, M., 1996. Contaminación de peces por metales pesados en el río Magdalena. Licania arborea 1 (1), 18–22.

Sakamoto, M., Ikegami, N., Nakano, A., 1996. Protective effects of Ca^{2+} channel blockers against methyl mercury toxicity. Pharmacol. Toxic. 78 (3), 193–199.

Santos-Francés, F., García-Sánchez, A.A.-R.P., Contreras, F., Adams, M., 2011. Distribution and mobility of mercury in soils of a gold mining region, Cuyuni river basin, Venezuela. J. Environ. Manage. 92, 1268–1276.

Sousa, C.J., Sampaio, D., Lemire, M., Fillion, M., Davée, J.R., Lucotte, M., Mergler, D., 2008. Daily mercury intake in fish-eating populations in the Brazilian Amazon. Nat. Publ. Group 18, 76–87.

Telmer, K., Veiga, M., 2008. World emissions of mercury from small scale artisanal gold mining and the knowledge gaps about them. In: Mercury Fate and Transport in the Global Atmosphere: Measurements, Models and Policy Implications.UNEP – United Nations Environment Programme, pp. 96–129 (Chapter 6).

Ullrich, S., Tanton, T., Abdrashitova, S., 2001. Mercury in the aquatic environment: a review of factors affecting methylation. Crit. Rev. Environ. Sci. Technol. 31, 241–293.

UNEP, 2013. United Nations Environment Programme: Global Mercury Assessment: Sources, Emissions, Releases, and Environmental Transport.

UNIDO, 2011. United Nations Industrial Development Organization: Annual Report 2010, Vienna.

UPME, 2005. Unidad de Planeación Minero Energética: Alteraciones neurocomportamentales en personas expuestas a mercurio en la actividad minera del oro en el municipio de Segovia (Antioquia). Contrato No. 1517-06-2005, Bogotá: República de Colombia Ministerio de Minas y Energía.

USEPA, 2001. United States Environmental Protection Agency: Human Health Criteria – Methylmercury Fish Tissue Criterion. <http://water.epa.gov/scitech/swguidance/standards/criteria/aqlife/methylmercury/factsheet.cfm#hh>.

USEPA, 2004. United States Environmental Protection Agency: What you need to know about mercury in fish and shellfish, EPA-823-R-04-005.

USEPA, 2011. United States Environmental Protection Agency: Integrated Risk Information System (IRIS). <http://www.epa.gov/iris>.

USEPA, 2013. United States Environmental Protection Agency: Integrated Risk Information System (IRIS). <http://www.epa.gov/iris/subst/0073.htm>.

Vasconcellos, M.B.A., Bode, P., Paletti, G., Catharino, M.G.M., Ammerlaan, A.K., Saiki, M., Fávaro, D.I.T., Byrne, A.R., Baruzzi, R., Rodrigues, D.A., 2000. Determination of mercury and selenium in hair samples of Brazilian Indian populations living in the Amazonic region by NAA. J. Radioanal. Nucl. Chem. 244 (1), 81–85.

Veiga, M., 2010. Antioquia, Colombia: the world's most polluted place by mercury: impressions from two field trips: University of British Columbia.

Veiga, M., Meech, J., 1995. Gold mining activities in the Amazon: clean-up techniques and remedial procedures for mercury pollution. Ambio 24 (6), 371–375.

Veiga, M., Baker, R., Bernaudat, L., Beinhoff, C., 2003. Mercury in artisanal gold mining and the Global Mercury Project. Urban Health Dev. Bull. 6, 12–20.

Velásquez-López, P., Veiga, M., Hall, K., 2010. Mercury balance in amalgamation in artisanal and small-scale gold mining: identifying strategies for reducing environmental pollution in Portovelo-Zaruma, Ecuador. J. Clean Prod. 18, 226–232.

WHO, 2000. World Health Organization: Air Quality Guidelines for Europe, second ed., Copenhagen: WHO Regional Publications, European Series, No. 91.

WHO/UNEP, 1976. World Health Organization/United Nations Environment Programme: International programme on chemical safety. Environmental Health Criteria 1: Mercury. Geneva: World Health Organization.

Yoneda, S., Suzuki, K., 1997. Detoxification of mercury by selenium by binding of equimolar Hg–Se complex to a specific plasma protein. Toxicol. Appl. Pharmacol. 143, 274–280.