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Organochlorine chemicals and neurodegeneration among elderly subjects in Costa Rica



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ARTICLE INFO

Article history:

Received 11 May 2014

Received in revised form

13 July 2014

Accepted 30 July 2014

Keywords:

Pesticides

Organochlorines

Parkinson's disease

Cognition

Costa Rica

ABSTRACT

Background: We previously screened 400 elderly Costa Ricans for neurodegenerative disease. Those reporting occupational pesticide exposure (18%) had an increased Parkinson's disease (PD) risk (OR 2.57, 95% CI 0.91–7.26), and worse cognition (Mini-Mental States Exam (MMSE) 24.5 versus 25.9 points, $p=0.01$). We subsequently measured long-lasting organochlorine pesticides (β -HCH, DDE, DDT, and dieldrin) in a sub-sample ($n=89$). Dieldrin and β -HCH have been linked to PD, and DDE to Alzheimer's disease.

Methods: We ran regression models for MMSE and tremor-at-rest to assess associations with pesticides in 89 subjects.

Results: The percent of β -HCH, DDE, DDT (parent compound for DDE), and dieldrin above their limit of detection (LOD) were 100%, 93%, 75%, and 57%, respectively. Tremor-at-rest was found in 21 subjects, and the mean MMSE was 25. Those who reported occupational pesticide exposure ($n=36$) had more detectable dieldrin samples ($p=0.005$), and higher mean levels of dieldrin ($p=0.01$), than those not reporting exposure. Other pesticides did not differ between those with and without self-reported occupational exposure. There was a positive but non-significant trend of higher risk for tremor-at-rest with higher dieldrin ($p=0.10$ for linear trend). Neither DDE nor DDT showed a relationship with MMSE. However, after excluding two outliers with the lowest MMSE scores, higher DDT levels showed some modest association with lower MMSE ($p=0.09$ for linear trend).

Conclusions: Our data are limited by small sample size. However, dieldrin was high in our population, has been previously linked to PD, and could be partly responsible for the excess PD risk seen in our population.

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1. Introduction

Exposure to pesticides, primarily occupational exposure, has been studied in relation to Parkinson's disease (PD) in over 40 epidemiologic studies, which have been reviewed in meta-analyses by Van der Mark et al. (2012) and Allen and Levy (2013); these authors found overall relative risks of 1.62 (95% CI 1.40–1.88) and 1.42 (1.32–1.52), respectively. Two recent studies have identified specific long-lasting organochlorine pesticides (β -HCH, dieldrin) as increasing risk (Richardson et al., 2011; Weisskopf et al., 2010), while two others have identified paraquat and/or rotenone (Tanner et al., 2011; Costello et al., 2009). Recently the fungicide benomyl has been associated with PD (Fitzmaurice

et al., 2013). Other recent work has identified organophosphates (OPs) (diazinon, chlorpyrifos, and parathion) as increasing PD risk when associated with a genetic variant (PON1) in the metabolism of OPs (Manthripragada et al., 2010; Lee et al., 2013). However, despite these advances, the specific pesticides implicated in PD have not been conclusively identified. A recent review (Pezzoli and Cereda 2013) concluded that “the literature supports the hypothesis that exposure to pesticides or solvents is a risk factor for PD” but noted that future “studies should also focus on specific chemical agents”.

Exposure to pesticides has also been linked to Alzheimer's disease (AD), although there are less data than for PD. Zaganas et al. (2013) recently reviewed 14 studies, regarding poor cognition or clinical disease, and concluded that the link with pesticides was suggestive, particularly for worse cognition. Recently Richardson et al. (2014) reported that DDE, a metabolite of DDT, was

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significantly higher in AD patients than controls. The highest tertile of DDE levels was associated with an odds ratio of 4.18 for increased risk for AD (95% CI, 2.54–5.82; $p=0.001$). These authors noted that exposure of human neuroblastoma cells to DDT or DDE increased levels of amyloid precursor protein.

To investigate these links further we recently screened 400 elderly subjects (age > 65) in Costa Rica for cognitive or motor deficits during 2011 (Steenland et al., 2013; Wesseling et al., 2013). These subjects were attending routine annual free medical exams; more than two-thirds of Costa Ricans over age 65 take advantage of these exams. Costa Rica is 41% rural. It has the highest per-capita use of pesticides in Central America, three times the average of the region (Bravo et al., 2011). Census data of 1984 indicated that 35% of the economically active population worked in agriculture, of whom virtually all were exposed to pesticides (Wesseling et al., 2001).

In our screening study, 18% reported past agricultural occupation with pesticide exposure. These pesticide-exposed subjects had an increased risk of PD (OR=2.57, 95% CI 0.91–7.26), whereas no excess risk was found for a diagnosis of AD or mild cognitive impairment (Steenland et al., 2013). Of our screened subjects, 92% failed Step 1 tests, which consisted of a 3 item-recall test and animal recognition test for cognition, and self-reported tremor/balance problems and a spiral drawing tests for motor deficits (Wesseling et al., 2013). Those who failed Step 1 tests passed on to screening Step 2, which consisted of a physician administering the Mini-mental State Exam (MMSE) for cognition and the Unified PD Rating Scale (UPDRS) for movement disorders; physicians were blinded to pesticide exposure status. Step 3 of the screening, for those who failed Step 2, consisted of an exam by a neurologist and a definitive diagnosis.

Regarding Step 2 tests (the outcomes in the present study), subjects with self-reported occupational pesticide exposure performed worse on the MMSE than those without occupational pesticide exposure (24.5 versus 25.9 points, $p=0.01$). Those who reported having used pesticides had also significantly elevated risks of abnormal scores on two UPDRS items, tremor-at-rest (OR 2.58, 1.28–5.23), and finger-tapping (OR=2.94, 95% CI 1.03–8.41). Tremor-at-rest is a cardinal sign of PD. Thirty-three (23%) of those examined by the neurologist in Step 3 of the screening were diagnosed with possible/probable PD, 3–4 times the expected based on international data; 88% of these cases had not been previously diagnosed.

To explore further these findings, we collected blood samples from a subsample of the screened subjects during January–February of the subsequent year 2012, when subjects returned for their yearly examination, to compare organochlorine residue levels between a group of subjects with past pesticide exposures and a group without such exposures and to analyze possible relationships of these residues with tremor-at-rest and the MMSE.

2. Methods

2.1. Recruitment of study population

We recruited subjects as they returned for their annual visits in the year after our initial study. Our goal was to recruit 100 subjects, approximately half of them with reported occupational exposure to pesticides. Since only 18% of the subjects had self-reported pesticide exposure, we oversampled this group. Eleven subjects were recruited who eventually could not be included in the analysis due to missing data. Of the remaining 89 subjects, 36 (40%) had reported occupational pesticide exposure and 53 (60%) had not.

Comparing 89 subjects with data on pesticide levels to those for whom we did not have pesticide levels but were part of the study population included in the original study ($n=311$), the mean age and years of education did not differ significantly.

2.2. Laboratory methods

After obtaining IRB approvals in the United States (Emory University) and Costa Rica (Universidad Nacional and Social Security of Costa Rica), we obtained consent from the recruited subjects to obtain a blood sample at the clinic. The serum fraction was separated and a 1-mL aliquot was taken for analysis. Samples were spiked with isotopically labeled p,p' -DDT and p,p' -DDE analogs, homogenized, denatured and extracted in Costa Rica using a slight modification of the method of Barr et al. (2006).

Samples were sent to Emory for analysis. The analytes were separated and analyzed using gas chromatography–tandem mass spectrometry using a modification of the method of Barr et al. (2003) adapted for a triple quadrupole mass spectrometer (Agilent Technologies, Santa Clara, CA). Injections of 2 μ L were used. A full calibration plot, unknowns, blanks and quality control materials were included in each analytic run. Samples were quantified using isotope dilution calibration. The limits of detection (LOD) were dieldrin (0.25 ng/mL); o,p -DDT (0.05 ng/mL); p,p' -DDT (0.05 ng/mL); o,p -DDE (0.05 ng/mL); p,p' -DDE (0.05 ng/mL) and β -HCH (0.1). The LOD was much higher than expected for dieldrin likely because of the lack of an isotopically labeled internal standard.

2.3. Statistical methods

We first analyzed whether subjects who had reported pesticide exposures had more samples above the LOD than those who had not reported exposure to pesticides. We then imputed values for samples below the LOD, by estimating an underlying log-normal distribution and drawing random samples from it (Finkelstein and Verma 2001).

Two sample t -tests were used to compare the group who had reported occupational pesticide exposure to the non-exposed group for pesticide levels, after taking the natural log of the pesticide levels (including imputed values) to ensure normality. Spearman correlation coefficients were calculated between pairs of pesticides. We regressed MMSE on pesticide levels using linear regression, adjusting for gender, age, and years of school. Continuous variables were used for age and years of schooling after categorical analyses indicating monotonic trends (inverse and positive, respectively) between these variables and MMSE. We did not collect data on other potential confounders of interest, such as body mass index or pregnancy history, as our study was a screening study, not designed for detailed questionnaires, and the time available with nurses for additional questions during the initial screening step was quite limited. We conducted an analysis by quartiles for each pesticide, and a test of trend via inclusion of a single (continuous) linear term. The referent for the quartile analyses was the lowest quartile for β -HCH, DDE, and DDT. For dieldrin, which has 43% samples below the LOD, use of the lowest quartile as a referent would not be recommended as values below the LOD were randomly assigned to those below the LOD. Therefore for dieldrin we used those values which were below the LOD as the referent, and constructed quartiles above the referent. Analyses were conducted separately for each pesticide. Data were sparse and models including all pesticides together were unstable; some pesticides were moderately correlated increasing instability.

We also ran logistic models for tremor-at-rest (yes/no), which was one of the 10 tests on the UPDRS, and the one most closely linked to a subsequent diagnosis of PD in our original larger population (the relative odds of PD for those with tremor vs. those without was 3.55 (95% CI 1.62–0.777)). Tremor-at-rest test had values of either 0 (no tremor), or 1 (some tremor), or 2 (more pronounced tremor). As only two subjects had a value of 2, we analyzed tremor-at-rest as either 0 (75%) or 1 (scores 1 or 2 combined; 25%); 21 of 89 subjects had a positive tremor-at-rest. Logistic models were adjusted for age and gender. Age was first considered as a categorical variable (quartiles) and showed a monotonic increasing trend with tremor; hence we included age as a continuous variable in final models. Years of school were not a predictor of tremor, and were not included in final models. Tremor-at-rest was regressed on 4 pesticides individually. Again, we conducted an analysis by quartiles for each pesticide, and a test of trend via inclusion of a single linear term. The referent for the quartile analyses was again the lowest quartile for β -HCH, DDE, and DDT, while for dieldrin we used those below the LOD as the referent, and constructed quartiles above the referent.

We also compared levels of the four pesticides to levels in US population, obtained from the NHANES 2003/2004 survey http://www.n.cdc.gov/nchs/nhanes/search/nhanes03_04.aspx for approximately 1800 subjects, chosen to represent the US population. We report the 25th, 50th, and 75th percentile of the distribution of each pesticide in our population and the NHANES population, using imputed data from our population when needed (for samples below the LOD), and also report the percent of samples below the LOD in each population.

3. Results

Table 1 shows the distribution of demographic data and pesticide levels for the subjects who had self-reported occupational pesticide exposure and those who had not. Pesticide users

and non-users did not differ by age. Those who had reported past pesticide exposure were more likely to be male and had lower years of education than those who did not, reflecting more rural and agricultural origins.

Table 1 also shows the levels of pesticides measured in our population. The percent of samples below the LOD were appreciable for dieldrin (43%) and DDT (22%), but minimal for DDE (7%) and β -HCH (0%). The percent below the LOD for those who reported pesticide use and those who did not report pesticide use did not differ for any pesticide other than dieldrin, where those reporting occupational pesticide exposure had significantly fewer samples below the LOD ($p=0.005$) than those not so reporting. Table 1 also presents the mean levels (medians are given in Table 2) of pesticides in the serum of those reporting occupational pesticide ($n=36$) and those not so reporting ($n=53$) in our population, using continuous data with imputation for samples below the LOD. The only pesticide that differed significantly between the two groups in our study was dieldrin, with those reporting pesticide use having higher levels ($p=0.01$, using the log of pesticide levels). Comparing the means in Table 1 (combined groups) with the median levels given in Table 2, means and medians differ markedly only for dieldrin, which were highly skewed with some very high values.

Spearman correlations between the four pesticides were only moderate (data not shown), the three highest being for DDT being positively correlated with dieldrin (0.27), DDE (0.23), and β -HCH (0.32), all significant at 0.05 level.

Table 2 shows the levels of pesticides found in our population and also shows comparable data from the US NHANES survey of 2003–2004, for subjects aged 50+ who would have been approximately the same age as our Costa Rican population in 2012. It is clear from Table 2 that β -HCH, and particularly dieldrin, were elevated in the Costa Rican population compared to the NHANES population, while DDT and DDE were not. The median dieldrin level in our population was 27 times higher than the median dieldrin level in NHANES subjects aged 50+ in 2003–2004. Aldrin (which metabolizes to dieldrin) and dieldrin were used in coffee farms in the study area, north of San Jose, until its ban in 1981; β -HCH was used only in a limited manner in some coffee storage areas (Dirección General de Investigaciones Agrícolas, 1974, and personal communication, Dr. Wesseling). DDT was mostly used for vector control in Costa Rica, but not in our malaria-free study area.

Table 3 presents the associations between the four pesticides and tremor-at-rest. No association was seen for β -HCH, DDT, or DDE. Dieldrin as a continuous variable (linear term) showed a positive but non-significant trend in risk for tremor ($p=0.10$). Quartile analyses for dieldrin (quartiles formed for those above the LOD) did not show a consistent monotonic trend, but those in the highest quartile had an elevated odds ratio of 2.42, which is likely to be the cause of the positive linear trend using a continuous variable.

Results for MMSE (Table 4) showed no associations between pesticides and MMSE. However, after removing the two lowest MMSE scores (7, 13), which were also the biggest outliers as per studentized residuals in the regression, increasing DDT showed a non-significant association with low MMSE scores ($p=0.09$), although quartile analyses did not show a consistent inverse trend. Supplemental analyses (not shown) defining the uppermost DDT category as the top 20% or 10% showed greater predicted drops in MMSE for these uppermost groups, indicating that those with the highest DDT were driving the inverse trend.

Table 2

Serum organochlorine pesticide levels in Costa Rica in 2012 ($n=89$) and NHANES in 2003–2004 ($n=1888$).

Pesticide (ng/ml)	Costa Rica ^a				NHANES age > 50 ^b			
	< LOD (%) ^{***}	25%	50%	75%	< LOD (%) ^{****}	25%	50%	75%
β -HCH	0	0.59	0.71	0.87	31	0.06	0.12	0.21
Dieldrin	47	0.07	1.63	4.87	10	0.04	0.06	0.09
p,p' -DDT	25	0.09	0.13	0.18	18	0.04	0.06	0.11
p,p' -DDE	7	0.27	0.67	1.25	0	2.32	5.10	10.12

^a Average age 76 in 2012.

^b 1888, 1859, 1978, and 1300 NHANES samples in 2003–2004 for β -HCH, p,p' -DDT, p,p' -DDE, and dieldrin, respectively. Average age 67 in 2003–2004.

^{***} LODs in Costa Rican samples for β -HCH, p,p' -DDT and p,p' -DDE, and dieldrin were 0.10, 0.05, and 0.05, and 0.25 ng/ml, respectively. Values below LOD imputed assuming a log normal distribution, in order to calculate percentiles. Higher percentage of values below LOD for dieldrin in Costa Rica vs. NHANES results from higher LOD in Costa Rica analyses.

^{****} LOD in NHANES varied by batches, but were approximately 0.09, 0.02, 0.02, and 0.02 for β -HCH, DDT, DDE, and dieldrin, respectively. No samples for DDE in NHANES were below the LOD. Samples below LOD were divided by the square root of 2 for calculating percentiles.

Table 1

Demographic and pesticide results for 89 subjects with measured pesticide levels.

Characteristic	Report of past occupational pesticide exposure ($n=36$)	Report of no past occupational pesticide exposure ($n=53$)	Combined population ($n=89$)	p -Value pesticide exposure vs. no pesticide exposure ^{***}
% male	86%	70%	76%	$p=0.08$
Mean year birth (s.d.)	74 (6)	73 (6)	74 (6)	$p=0.56$
Mean years of school (s.d.)	4.4 (3.4)	7.3 (5.2)	6.1 (4.7)	$p=0.002$
% p,p' -DDE < LOD ^a	3%	9%	7%	$p=0.22$
% p,p' -DDT < LOD ^a	16%	26%	22%	$p=0.28$
% dieldrin < LOD ^a	25%	55%	43%	$p=0.005$
% β -HCH < LOD ^a	0%	0%	0%	$p=0.99$
Mean p,p' -DDE (s.d.) ^{**}	0.70 (0.55)	1.20 (1.46)	1.00 (1.20)	$p=0.50$
Mean p,p' -DDT (s.d.) ^{**}	0.14 (0.08)	0.12 (0.12)	0.08 (3.74)	$p=0.08$
Mean dieldrin (s.d.) ^{**}	7.58 (19.63)	3.40 (6.48)	5.09 (13.50)	$p=0.01$
Mean β -HCH (s.d.)	0.78 (0.30)	0.73 (0.19)	0.75 (0.24)	$p=0.69$

^a LODs for β -HCH, dieldrin, p,p' -DDT and p,p' -DDE, were 0.10, 0.25, 0.05, and 0.05 ng/ml, respectively.

^{**} Units are ng/ml. Means calculated using imputed values for values of p,p' -DDE, p,p' -DDT, and dieldrin below LOD.

^{***} p -Values based on chi-square test for categorical data, and t -test using the log of pesticide values for comparison of means.

Table 3
Results from logistic regression models for UPDRS tremor-at-rest and four pesticides^a.

Pesticide (ng/ml)	OR (95% CI)				Direction and test for linear trend (p-Value)
	Quartile 1 (referent)	Quartile 2 ^{**}	Quartile 3	Quartile 4	
β-HCH	1	0.70 (0.13–3.75)	2.21 (0.51–9.53)	1.46 (0.32–6.63)	(+), p=0.67
p,p'-DDE	1	0.23 (0.05–1.20)	0.55 (0.12–2.44)	0.66 (0.17–2.56)	(–), p=0.68
p,p'-DDT	1	0.72 (0.16–3.21)	0.72 (0.14–3.75)	1.77 (0.46–6.75)	(+), p=0.52
Dieldrin	< LOD (referent)	Quartile 1	Quartile 2	Quartile 3	Quartile 4
	1	No estimate ^{***}	1.06 (0.22–5.10)	0.52 (0.09–2.89)	2.42(0.56–10.58) (+), p=0.10

^a Adjusted for age (continuous) and gender. 21/89 subjects had tremor-at-rest.

^{**} Cutpoints for β-HCH were 0.59, 0.71 and 0.88 ng/ml. Cutpoints for DDE were 0.27, 0.69, and 1.26 ng/ml. Cutpoints for DDT were 0.09, 0.13, and 0.17. Cutpoints for dieldrin above the LOD (0.25 ng/ml) were 2.14, 3.88, and 7.98.

^{***} No cases of tremor in this quartile.

Table 4
Results from linear regression models for MMSE and four pesticides^a.

Pesticide (ng/ml)	β (95% CI)				Direction and test for trend (p-Value) ^{**}
	Quartile 1 (referent)	Quartile 2 coefficient (se)	Quartile 3 coefficient (se)	Quartile 4 coefficient (se)	
β-HCH	0	0.63 (1.26)	1.26 (1.26)	–0.86 (1.31)	(–), p=0.62
p,p'-DDE	0	1.32(1.27)	–0.38 (1.33)	1.37 (1.27)	(+), p=0.52
p,p'-DDT	0	1.40 (1.24)	1.51 (1.35)	0.88 (1.25)	(–), p=0.75
p,p'-DDT (without 2 outliers)	0	0.38 (1.07)	0.49 (1.17)	–0.44 (1.09)	(–), p=0.09
(referent)	< LOD(referent)	Quartile 1	Quartile 2	Quartile 3	Quartile 4
Dieldrin	0	–2.75 (1.48)	–0.06 (1.35)	0.08 (1.31)	–0.17 (1.36) (+), p=0.94

^a Adjusted for age (continuous), years of schooling (continuous), and gender. Cutpoints for quartiles given in footnote to Table 3

4. Discussion

While our sample size is small, it is clear that dieldrin, and to a lesser extent β-HCH, showed high levels compared to what might be expected based on NHANES data from 2003–2004. Both these pesticides have been associated with PD in past studies (Richardson et al., 2011; Weisskopf et al., 2010), and in our earlier study in this population (400 subjects) we found that occupational pesticide exposure had a 2.6 fold risk for PD. Dieldrin is known to have been used in our study area.

We did not find elevated levels of DDT or DDE in our population, compared to NHANES data. This is probably due to the fact that DDT and DDE were not used for vector control in the area where we conducted our study, and were not used on crops in the area.

Those reporting past occupational pesticide exposure showed significantly higher levels of dieldrin than those not reporting such exposure, while the other three pesticides did not differ between those reporting and not-reporting occupational exposure. A limitation here is that self-reports of occupational exposure may be inaccurate, and memory of such exposure might be affected in those with worse cognition (including those with Parkinson's disease, which sometimes entails worse cognition).

In the current study those with the highest levels of dieldrin showed some evidence of an excess risk of tremor-at-rest during the UPDRS exam, although a trend test did not reach statistical significance at 0.05 level. Our findings are limited by a small sample size and cross-sectional design. It seems possible, nonetheless, that dieldrin may be partly responsible for the elevated PD risk seen in our earlier work with this population. Caution is needed because we obtained blood samples of only a portion of our original population (89/400). Furthermore, we were not able to take into account possible non-occupational exposure to pesticides. In addition, other pesticide exposure in the past could easily play a role; in particular paraquat and organophosphates that have been commonly used in the study area in Costa Rica and have been

associated with PD in the literature. We did not measure these short-lived pesticides in the blood.

We found a very modest association between DDT and worse MMSE scores in this population, but only after taking out two outliers with lowest MMSE scores; the negative effect was limited to those with the highest DDT exposure. DDT is the parent compound for DDE, for which we found no association with MMSE; it is not clear why we would have found this signal for DDT but not for DDE. Both were found in vitro to increase beta-amyloid protein in neurons; beta-amyloid is an important constituent of plaques in AD (Richardson et al., 2014). Moreover, Richardson et al. (2014) found that DDE was significantly higher in AD cases vs. controls, although they did not report any analogous data for DDT. We did not find an association between DDE and cognition. Given the weakness of the finding for DDT and the lack of any signal for DDE, it is possible that DDT findings were due to chance.

In summary, we have found high blood levels of dieldrin in a sample of our previously studied population, and those reporting past occupational exposure to pesticides had significantly higher levels than those reporting no occupational exposure. There was also some modest suggestion of an association between higher dieldrin and more tremor-at-rest, a cardinal sign of PD. The primary limitation of our study was small sample size.

Acknowledgment

This work was supported by a pilot grant from the Emory Alzheimer's Disease Research Center (ADRC)(NIH-NIA 5 P50 AG025688). Laboratory analyses were supposed via an NIEHS Center Grant (Hercules), grant # P30 ES019776.

References

Allen, MT, Levy, LS., 2013. Parkinson's disease and pesticide exposure – a new assessment. *Crit. Rev. Toxicol.* 43 (6), 515–534 (Jul).

- Barr, JR, Maggio, VL, Barr, DB, Turner, WE, Sjödin, A, Sandau, CD, Pirkle, JL, Needham, LL, Patterson Jr., DG, 2003. New high-resolution mass spectrometric approach for the measurement of polychlorinated biphenyls and organochlorine pesticides in human serum. *J. Chromatogr. B Anal. Technol. Biomed. Life Sci.* 794 (1), 137–148 (Aug 25).
- Barr, DB, Weihe, P, Davis, MD, Needham, LL, Grandjean, P., 2006. Serum polychlorinated biphenyl and organochlorine insecticide concentrations in a Faroese birth cohort. *Chemosphere* 62 (7), 1167–1182.
- Bravo, V, Rodríguez, T, van Wendel de, Joode B, Canto, N, Calderón, GR, Turcios, M, Menéndez, LA, Mejía, W, Tatis, A, Abrego, FZ, de la, Cruz E, Wesseling, C, 2011. Monitoring pesticide use and associated health hazards in Central America. *Int. J. Occup. Environ. Health* 17, 258–269.
- Costello, S, Cockburn, M, Bronstein, J, Zhang, X, Ritz, B., 2009. Parkinson's disease and residential exposure to maneb and paraquat from agricultural applications in the central valley of California. *Am. J. Epidemiol.* 169, 919–926.
- Fitzmaurice, A.G., Rhodes, S.L., Lulla, A., Murphy, N.P., Lam, H.A., O'Donnell, K.C., Barnhill, L., Casida, J.E., Cockburn, M., Sagasti, A., Stahl, M.C., Maidment, N.T., Ritz, B., Bronstein, J.M., 2013. Aldehyde dehydrogenase inhibition as a pathogenic mechanism in Parkinson disease. *Proc. Natl. Acad. Sci.* 110 (2), 636–641.
- Finkelstein, MM, Verma, DK., 2001. Exposure estimation in the presence of nondetectable values: another look. *AIHAJ* 62 (2), 195–198 (Mar-Apr).
- Lee, PC, Rhodes, SL, Sinsheimer, JS, Bronstein, J, Ritz, B., 2013. Functional paraoxonase 1 variants modify the risk of Parkinson's disease due to organophosphate exposure. *Environ. Int.* 56, 42–47 (Jun).
- Manthripragada, AD, Costello, S, Cockburn, MG, Bronstein, JM, Ritz, B., 2010. Paraoxonase 1, agricultural organophosphate exposure, and Parkinson disease. *Epidemiology* 21 (1), 87–94 (Jan).
- Dirección General de Investigaciones Agrícolas, 1974. Manual de Recomendaciones, Cultivos Agrícolas de Costa Rica Ministerio de Agricultura y Ganadería, San José, Costa Rica p. page 288.
- Pezzoli, G, Cereda, E., 2013. Exposure to pesticides or solvents and risk of Parkinson disease. *Neurology* 80 (22), 2035–2041 (May 28).
- Richardson, J, Roy, A, Shalat, S, Buckley, B, Winnik, B, Gearing, M, Levey, A, Factor, S, O'Suilleabhain, P, German, D, 2011. β -hexachlorocyclohexane levels in serum and risk of Parkinson's disease. *Neurotoxicology* 32, 640–645.
- Richardson, JR, Roy, A, Shalat, SL, von Stein, RT, Hossain, MM, Buckley, B, Gearing, M, Levey, AI, German, DC, 2014. Elevated serum pesticide levels and risk for Alzheimer disease. *JAMA Neurol.* 71 (3), 284–290 (Mar).
- Steenland, K, Wesseling, C, Roman, N, Quiros, I, Juncos, J., 2013. Occupational pesticide exposure and screening tests for neurodegenerative disease among an elderly population in Costa Rica. *Environ. Res.* 120, 96–101.
- Tanner, CM, Kamel, F, Ross, GW, Hoppin, JA, Goldman, SM, Korell, M, Marras, C, Bhudhikanok, GS, Kasten, M, Chade, AR, Comyns, K, Richards, MB, Meng, C, Priestley, B, Fernandez, HH, Cambi, F, Umbach, DM, Blair, A, Sandler, DP, Langston, JW., 2011. Rotenone, paraquat, and Parkinson's disease. *Environ. Health Perspect.* 119, 866–872.
- Van der Mark, M, Brouwer, M, Kromhout, H, Nijssen, P, Huss, A, Vermeulen, R., 2012. Is pesticide use related to Parkinson's Disease? Some clues to heterogeneity in study results. *Environ. Health Perspect.* 120, 340–347.
- Wesseling, C, Aragón, A, Castillo, L, Corriols, M, Chaverri, F, de la Cruz, E, Keifer, M, Monge, P, Partanen, TJ, Ruepert, C, van Wendel de, Joode B, 2001. Hazardous pesticides in Central America. *Int. J. Occup. Environ. Health* 7, 287–294.
- Wesseling, C, Román, N, Quirós, I, Páez, L, García, V, Mora, AM, Juncos, JL, Steenland, K, 2013. Parkinson's and Alzheimer's diseases in Costa Rica: a feasibility study toward a national screening program. *Glob. Health Action* 623061 (Dec 27)
- Weisskopf, MG, Knekt, P, O'Reilly, EJ, Lyytinen, J, Reunanen, A, Laden, F, Altshul, L, Ascherio, A., 2010. Persistent organochlorine pesticides in serum and risk of Parkinson disease. *Neurology* 74 (13), 1055–1061 (Mar 30).
- Zaganas, I, Kapetanaki, S, Mastorodemos, V, Kanavouras, K, Colosio, C, Wilks, MF, Tsatsakis, AM., 2013. Linking pesticide exposure and dementia: what is the evidence?. *Toxicology*, 3–11 (May 10)307, 3–11.