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Peripubertal serum concentrations of organochlorine pesticides and semen parameters in Russian young men

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\textbf{A R T I C L E  I N F O}

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\textbf{A B S T R A C T}

\textbf{Background:} Epidemiologic literature on the relation of organochlorine pesticides (OCPs) with semen quality among adult men has been inconclusive, and no studies have prospectively explored the association between peripubertal serum OCPs and semen parameters in young men.

\textbf{Objective:} To evaluate prospective associations of peripubertal serum concentrations of hexachlorobenzene (HCB), β-hexachlorocyclohexane (β-HCH), and p,p’-dichlorodiphenyldichloroethylene (p,p’-DDE) with semen parameters among young Russian men.

\textbf{Methods:} This prospective cohort study included 152 young men who enrolled in the Russian Children's Study (2003–2005) at age 8–9 years and were followed annually until young adulthood. HCB, β-HCH, and p,p’-DDE concentrations were measured at the CDC by mass spectrometry in serum collected at enrollment. Between 18 and 23 years, semen samples (n = 298) were provided for analysis of volume, concentration, and progressive motility; we also calculated total sperm count and total progressive motile count. Linear mixed models were used to examine the longitudinal associations of quartiles of serum HCB, β-HCH and p,p’-DDE with semen parameters, adjusting for total serum lipids, body mass index, smoking, abstinence time and baseline dietary macronutrient intake.

\textbf{Results:} Lipid-adjusted medians (IQR) for serum HCB, β-HCH and p,p’-DDE, respectively, were 150 ng/g lipid (102–243), 172 ng/g lipid (120–257) and 275 ng/g lipid (190–465). In adjusted models, we observed lower ejaculated volume with higher serum concentrations of HCB and β-HCH, along with reduced progressive motility with higher concentrations of β-HCH and p,p’-DDE. Men in the highest quartile of serum HCB had a mean (95% CI) ejaculated volume of 2.25 mL (1.89, 2.60), as compared to those in the lowest quartile with a mean (95% CI) of 2.97 mL (2.46, 3.49) (p = 0.03). Also, men in the highest quartile of serum p,p’-DDE had a mean (95% CI) progressive motility of 51.1% (48.6, 53.7), as compared to those in the lowest quartile with a mean (95% CI) of 55.1% (51.7, 58.5) (p = 0.07).

\textbf{Conclusion:} In this longitudinal Russian cohort study, peripubertal serum concentrations of selected OCPs were associated with lower ejaculated volume and progressive motility highlighting the importance of the peripubertal window when evaluating chemical exposures in relation to semen quality.

\begin{thebibliography}{9}
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1. Introduction

Meta-analyses have documented downward trends in sperm concentration and total sperm count among fertile men from 1934 to 2013 (Levine et al., 2017; Swan et al., 2000). Semen quality is used for diagnosis of male infertility (Jequier, 2011). Compared to men with good semen quality, those with poor semen quality had a higher risk of common chronic diseases (Eisenberg et al., 2014; Latif et al., 2017) and mortality (Eisenberg et al., 2014; Jensen et al., 2009), highlighting the role of semen quality as a marker for broad health beyond fertility and reproduction. Therefore, identifying modifiable factors, such as environmental and dietary exposures, that can predict semen parameters has become a major clinical and public health matter (Minguez-Alarcon et al., 2018).

Organochlorine pesticides (OCPs), such as hexachlorobenzene (HCB), β-hexachlorocyclohexane (βHCH), and 1,1,1-trichloro-2,2,2-bis(p-chlorophenyl)ethane (DDT), are persistent chlorinated compounds that have been associated with semen quality in epidemiological studies (Ayotte et al., 2001; De Jager et al., 2006; Faure et al., 2014; Paoli et al., 2015; Toft et al., 2006). Historically, they were widely used as insecticides and fungicides, and played an important role in the control of public health epidemics such as typhus and malaria (Genuis et al., 2016). Because of their ecosystem harm, environmental persistence and adverse health effects (Barber et al., 2005; Costa, 2015; UN, 2009), the use of OCPs is currently banned in most countries worldwide, especially the United States and Europe (UN, 2001; USEPA, 2016). However, they are still used as pesticides in limited regions in Asia, Africa and parts of Central and South America (FAO, 2005; Gupta, 2004; Haylamicheal and Dalvie, 2009). OCPs have low polarity and are poorly soluble in water, but are lipophilic (Longnecker, 2005; Wolff et al., 2000). Main factors that facilitate these OCPs to persist and bioaccumulate include their very long half-life, up to years, and their resistance to degradation in contaminated soils and sediments (Wauchoppe et al., 1992). While ingestion of contaminated food represents the main human exposure source, OCPs exposure through contaminated water, soil, dust, and, to a lesser extent air, is also possible (ATSDR, 2019; Barber et al., 2005). OCPs have demonstrated endocrine disrupting activity in experimental models (Casals-Casas and Desvergne, 2011; Gray et al., 2001). However, epidemiological studies, most of them cross-sectional, exploring the association between serum concentrations of OCPs and semen quality in adult men have shown mixed results (Pant et al., 2013; Perry, 2008). Interestingly, no study to date has prospectively investigated the association between peripubertal serum concentrations of OCPs and semen parameters in young men. This research gap is particularly important since exposure to environmental pollutants during specific windows of testicular development (e.g. peripubertal period) has a negative impact on spermatogenesis, (Sutton et al., 2010) with potential consequences to semen quality.

Thus, we prospectively explored whether peripubertal serum concentration of HCB, βHCH and dichlorodiphenyldichloroethylene (p,p′-DDE), a metabolite of DDT, at 8–9 years are associated with semen parameters measured during young adulthood in young Russian men. Previous findings from the same cohort showed later pubertal onset among boys with higher serum HCB concentrations (Lam et al., 2014) and later age at attainment of sexual maturity among boys with higher serum HCB and βHCH (Lam et al., 2015). We have also previously reported that higher peripubertal serum dioxin concentrations were prospectively associated with lower semen parameters in this cohort (Minguez-Alarcon et al., 2017) and altered sperm DNA methylation (Pilsner et al., 2018).

2. Methods

2.1. Study population

Our study population consists of a subset of the 516 boys who were enrolled at 8 and 9 years old in the Russian Children’s Study (RCS). At enrollment, each male underwent a complete physical exam and their adult guardian completed health, dietary, and lifestyle surveys. Additionally, each consented participant had blood drawn for OCPs measurements. This initial assessment was followed by yearly physical exams and questionnaires as previously described (Hauser et al., 2008; Williams et al., 2010).

Out of the 516 boys initially enrolled between 2003 and 2005, 139 (26%) were lost to follow up by the time of the semen analysis either due to death (n = 6) or no longer residing in the study area (n = 129), and 4 were not invited to participate due to severe cognitive impairment (Fig. 1). Of the 377 remaining boys, 152 declined to participate in the semen study. Thus, 225 (48%) young men provided semen samples between 2012 and 2018. Additionally, 1 participant who were...
diagnosed with severe chronic disease, 1 azoospermic young man and 71 subjects with missing serum OCP concentrations were excluded from the subset in the OCP analysis, leaving a final study sample size of 152 young men who provided 1 to 2 semen samples (N total = 298) at age 18–23 years (Fig. 1).

The study was approved by the Human Studies Institutional Review Boards of the Chapaevsk Medical Association (Chapaevsk, Russia), Harvard T.H. Chan School of Public Health, Brigham and Women’s Hospital (Boston, MA, USA), and Nemours Health Care System (Wilmington, DE, USA). During the baseline assessment, the adult guardian/parent signed an informed consent, and each participant signed an assent before participation. Once participants were 18 years of age or older, they signed a consent form, including a separate consent for providing semen samples.

2.2. OCPs exposure assessment

During enrollment, fasting blood samples were collected, stored at −35 °C, and shipped to the National Center for Environmental Health at the Centers for Disease Control and Prevention (CDC; Atlanta, GA, USA) for analysis. Samples, including method blanks, and quality control samples were spiked with a mixture of 13C12-labeled pesticides as internal standards. Serum analytes were isolated by C18 solid-phase extraction (SPE), followed by a multicolumn automated cleanup, extraction and enrichment procedure (Sjödin et al., 2004; Turner et al., 1997). Analytes were separated using a DB-5 MS capillary column (Phenomenex, Torrance, CA, USA) and quantified using selected-ion-monitoring (SIM) high-resolution (10,000 resolving power) mass spectrometry (HRGC-ID/HRMS; Thermo Electron North America, LLC, West Palm Beach, FL, USA) (Barr et al., 2003; Patterson et al., 1987). Quantification was done by isotope dilution mass spectrometry using calibration standards containing 13C12-labeled and unlabeled analytes. The total serum lipid content of the sample was derived from enzymatic measurements of total cholesterol and triglycerides, then calculated using the Phillips equation (Phillips et al., 1989). Quality control sample coefficients of variation combining between/within-run reproducibility were generally between 10% and 15%. All study serum concentrations of HCB, βHCH, and p,p’-DDE were above the limit of detection. All OCP concentrations were expressed on a wet-weight basis (µg/g serum) or on a lipid-normalized basis (ng/g lipid) (division of wet-weight levels by lipid concentrations).

2.3. Semen parameters assessment

Each young man included in the study was asked to contribute a semen sample upon reaching 18 years of age or older using sexual abstinence of 2–4 days. After consent as described above, they each provided 1 to 2 semen samples by masturbation inside a dedicated room next to the study Andrology Lab for a total of 298 samples. Physician recorded information regarding any viral/bacterial illness or fever in the months prior to the semen collection and date/time of last recalled ejaculation for calculation of abstinence time. The samples were stored inside an incubator at 37 °C. After a maximum of one hour after sample collection, evaluation of semen parameters was carried out. Most samples (99%), however, were analyzed within a half hour of the collection. All samples were assessed by a single andrology technician (LS) and analyzed according to criteria updated by the Nordic Association for Andrology (NAFA) and European Society of Human Reproduction and Embryology—Special Interest Group in Andrology (ESHRE-SIGA) (Björdahl et al., 2010). The technician was blinded regarding serum OCPs concentrations of the subjects providing semen samples.

Semen volume was measured using a one, five, or ten mL disposable pipette. Sperm motility was evaluated by microscopic examination of the semen sample in duplicate at 400 times magnification. Results were reported following the 1999 WHO manual for the examination and processing of human semen. Specifically, at least 200 sperm per duplicate were classified into one of 4 categories: Class A: rapidly progressive motile; Class B: slowly progressive motile; Class C: locally motile and Class D: immotile. The total percent motile sperm of the sample was calculated by summing the individual percentages of the WHO classes A, B, and C of each sample (WHO, 2010). Sperm concentration was quantified using two aliquots and Improved Neubauer Chamber Hemacytometer (INCH) at 200 times magnification under a phase contrast microscope. Duplicates for sperm concentration and motility were assessed and compared. Differences between the duplicates did not exceed the acceptance limit in any of the samples. Specifically, within-observer mean coefficient of variation (CV) in duplicates was 6.7% for sperm concentration and 4.8% for progressive motility.

2.4. Statistical analysis

We calculated medians and interquartile ranges (IQR) for participant demographics, dietary and parental characteristics that were continuous variables, and number and percentages for categorical variables. Semen parameters were reported as medians (IQR). Serum OCP distributions were reported as mean and percentiles. Because OCPs are lipophilic and because of the potential for bias, rather than modeling lipid-normalized OCPs, we instead chose to use the wet weights for OCPs and adjust for concurrently measured serum total lipids by including this as a covariate in the model (Li et al., 2013; Schisterman et al., 2005). Serum OCP concentrations (wet-weight) were divided into quartiles, and the first (lowest) quartile was used as the reference group. Total sperm count (volume × sperm concentration), total motile sperm count (total sperm count × % motile sperm) and total progressive motile sperm count (total sperm count × % progressive motile sperm) were calculated. Total sperm count, sperm concentration and total motile sperm count were log-transformed to approximate a normal distribution. Linear regression models with random subject effects to account for repeated measurements within the same man were used to examine the relation between quartiles of serum OCPs concentrations and semen parameters. We compared semen parameters (total sperm count, sperm concentration, % progressive motile sperm, total progressive motile sperm count, and semen volume) among men with higher quartiles of serum OCPs concentrations to those within the lowest quartile. Predicted marginal means for these parameters were estimated as least square means (Searle et al., 1980) (adjusted for confounders at the mean level for continuous variables and for categorical variables weighted according to their frequencies) and were back-transformed to allow presentation of results in the original scale. Tests for linear trends were conducted using quartiles of serum OCPs concentrations as ordinal levels. Inverse probability of censoring weights (IPCW) were used to account for potential selection bias, based on fitting a logistic regression model to obtain predicted probabilities of having a semen sample available among the eligible men. Covariates included in the IPCW model were baseline measures of socioeconomic status and boy’s health measures [birthweight, breastfeeding weeks, body mass index (BMI), total calorie intake, beer intake, household smoking, and household income] (Supplemental Table 1).

Potential confounders included in the primary models for semen parameters were selected based on a priori evidence from the literature and supported empirically by associations with one or more of the semen parameters and/or serum concentrations of OCPs (> 10% in change of point estimate). In addition, we included abstinence time (days) in the fully adjusted models regardless of statistical significance since this is a well-known predictor of most semen quality parameters, and thus can improve the precision of the exposure estimates in the model (Schisterman et al., 2009). Based on these criteria, in the fully adjusted models we included total serum lipids (mg/dL), BMI (kg/m2), abstinence time (< 2 days, 2–5 days, ≥ 5 days), smoking status (yes vs no) and total calorie (kcal/day) intake, carbohydrates (% calories), and
fat (% calories) at age 8–9 years. Smoking status was collected using the question: “Have you smoked a cigarette, even a few puffs, within the past year?” prior to semen collection. To investigate the robustness of the findings, we performed sensitivity analyses excluding men who were diagnosed with cryptorchidism (n = 3), varicocele (n = 5) or orchiditis (n = 1) as well as further adjusting for serum concentrations of total dioxin and dioxin-like compounds toxic equivalents (total TEQs) (Minguez-Alarcon et al., 2017). We analyzed the data using SAS (version 9.4; SAS Institute Inc., Cary, NC, USA), and two-sided p-values ≤ 0.05 were considered statistically significant.

3. Results

Of the 298 semen samples collected from the 152 young men, 146 men (96%) provided 2 samples approximately one week apart, and 6 men (4%) provided one sample. All participants were Caucasian males, with a median (IQR) age at time of semen collection of 18.2 years (18.1–19.2) and a median (IQR) BMI of 21.2 (19.2–23.4) kg/m² (Table 1). Entry characteristics of those included in the analysis were similar to those not included, although they had slightly higher BMI (Supplemental Table 1). Median (IQR) values for semen parameters are summarized in Table 2. Median (IQR) abstinence time was 2.71 days (1.88, 3.92). Over half (52%) of the semen samples were above NAFAS-EHRE reference values for sperm counts (≥ 80 million) and motility (≥ 60%) (Björndahl et al., 2010).

None of the OCP concentrations were below the limit of detection in the serum samples collected at entry, when the boys were 8 to 9 years old (Table 3). Lipid-adjusted medians (IQR) for serum HCB, βHCH and p,p’-DDE, respectively, were 150 ng/g lipid (102–243), 172 ng/g lipid (120–257) and 275 ng/g lipid (190–465). Spearman correlations were moderate between serum concentrations of βHCH and p,p’-DDE (r = 0.56) and between serum HCB and βHCH (r = 0.66) along with reduced progressive motility with higher concentrations of p,p’-DDE (Table 4). For example, men in the highest quartile of serum HCB had lower ejaculated volume than those in the lowest quartile (mean = 2.25 mL vs 2.97 mL), corresponding to a 24% decrease in ejaculated volume (p = 0.03). Similarly, men in the highest quartile of serum p,p’-DDE had lower progressive motility as compared to those in the lowest quartile (51.1% vs 55.1%, p = 0.07). We found similar estimates in two sensitivity analyses; one excluding men who were diagnosed with cryptorchidism, varicocele or orchiditis (Supplemental Table 2) and other further adjusting for serum total TEQs concentrations (Supplemental Table 3), although associations with semen volume and motility became somewhat stronger after excluding participants diagnosed with the male reproductive conditions noted above (Supplemental Table 2).

4. Discussion

In this longitudinal study of 152 young Russian men contributing 298 semen samples, we explored prospective associations between peripubertal serum concentration of HCB, βHCH, and p,p’-DDE (at 8–9 years) and semen parameters measured approximately 10 years later. We found lower ejaculated volume with increased serum concentrations of HCB and βHCH. We also observed reduced progressive motility with increased serum concentrations of p,p’-DDE, however this association did not reach statistical significance. No other clear associations were found with any other semen parameters including sperm concentration. Previous findings from this study cohort shown associations between higher serum HCB levels and later age at attainment of sexual maturity (Lam et al., 2014), as well as higher prepubertal serum HCB and βHCH concentrations with later age at attainment of sexual maturity (Lam et al., 2015). Serum concentrations of OCPs reported in the Russian boys at ages 8–9 years were markedly higher than children in other populations. For example, compared to U.S. boys aged 12–19 years in the 2003–2004 National Health and Nutrition Examination Survey (NHANES) (CDC, 2019), RCS participants had approximately 4 times higher serum p,p’-DDE concentrations (mean of 461 ng/g vs. 105 ng/g). The differences were even more pronounced for serum HCB concentrations, with a mean of 217 ng/g in the RCS boys compared to a reported mean of 13.3 ng/g in 2003–2004 NHANES boys. Higher serum OCP concentrations were also found among our Russian boys compared to European boys in study cohorts in Belgium (Cros et al., 2015) and Germany (Becker et al., 2006).

Exposure to OCPs and male reproductive endpoints have been a
p,p′-DDE was shown to be hormonally active with the ability to decline in semen parameters in rats (Prasad et al., 1995). Furthermore, was associated with a decrease in testosterone levels and abnormal reproductive capacity has also been reported in the bald eagle (Haliaeetus leucocephalus) population in North America in relation to p,p′-DDE (Guillette and Guillette, 1996). Reduced anogenital distance, hypospadias, and cryptorchidism were found in rats exposed during the fetal period to vinclozolin, p,p′-DDE and procymidine (Gray et al., 2001). Impaired reproductive capacity has also been reported in the bald eagle (Haliaeetus leucocephalus) population in North America in relation to p,p′-DDE exposure (Bowerman et al., 1995). More specifically, HCH exposure was associated with a decrease in testosterone levels and abnormal decline in semen parameters in rats (Prasad et al., 1995). Furthermore, p,p′-DDE was shown to be hormonally active with the ability to penetrate the blood-testis barriers, thus potentially modulating spermatogenesis and its micro-milieu (Bush et al., 1986; Tuohimaa and Wichmann, 1985).

Whether exposure to OCPs is associated with negative semen quality in humans is less clear. Despite a multitude of studies exploring the relationship between OCPs and semen parameters in humans, findings have been inconsistent so far. These epidemiological studies varied greatly in their methods, and most of them had a cross-sectional design (Perry, 2008). OCPs such as (p,p′-DDE) and other organochlorine compounds such as 2,2’,4,4’,5,5’-hexachlorobiphenyl have been associated with lower sperm motility in a cross-sectional study in Ukraine (Toft et al., 2006) and reduced couples’ fecundity measured as time to pregnancy in a prospective cohort (Buck Louis et al., 2013). In some cross-sectional studies, p,p′-DDE has been associated with lower sperm count and volume (Ayotte et al., 2001) and abnormal morphology (De Jager et al., 2006), and also higher levels of p,p′-DDE were found in the semen of infertile men (Pant et al., 2013). Although, Hauser and colleagues initially observed negative associations of PCBs and p,p′-DDE with sperm motility, concentration and morphology in a cross-sectional pilot study of 29 men recruited from the Massachusetts General Hospital (MGH) Andrology Laboratory (Hauser et al., 2002), they did not confirm the negative associations in a subsequent larger study of 212 men (Hauser et al., 2003). Serum p,p′-DDE was associated with a decrease in seminal volume and concentration in a cross-sectional Mexican study (Ayotte et al., 2001). This study was limited by its small sample size (N = 24 men) and extremely high serum concentrations of p,p′-DDE (up to 77900 ng/g). Multiple studies have found no relationship between OCPs and semen parameters (Bush et al., 1986; Tuohimaa and Wichmann, 1985).
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Author Contributions

Dr. Abou Ghayda, Sergeyev and Mínguez-Alarcón had full access to all of the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis. Study concept and design: Abou Ghayda, Sergeyev, Hauser and Mínguez-Alarcón. Acquisition of data: Sergeyev, Smigulina, Dikov. Analysis of data: Abou Ghayda and Mínguez-Alarcón. Interpretation of data: All authors. Drafting of the manuscript: Abou Ghayda and Mínguez-Alarcón. Critical revision of the manuscript for important intellectual content: All authors.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2020.106085.

References

