Exposure to Environmental Endocrine Disruptors and Child Development

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Exposure to exogenous chemicals can affect endocrine function at multiple sites and through numerous specific modes of action, which may have far-reaching effects on human health and development. Widespread human exposure to known or suspected endocrine disrupting chemicals (EDCs) has been documented in the United States and worldwide, as have trends for increased rates of endocrine-related diseases and disorders among children. While human epidemiology studies of exposure to EDCs and children’s health remain extremely limited, a growing body of evidence shows that exposure to a number of chemicals commonly found in consumer goods, personal care products, food, drinking water, and other sources may adversely affect child development through altered endocrine function. This narrative review provides a brief introduction to several common EDCs (with a specific focus on persistent organic pollutants, phthalates, bisphenol A, and contemporary-use pesticides, which represent only a small number of all known or suspected EDCs), an overview of the state of the human evidence for adverse effects of EDCs on child development (fetal growth, early reproductive tract development, pubertal development, neurodevelopment, and obesity), guidance for health care providers based on current knowledge, and recommendations for future research.


The development and use of synthetic chemicals have grown exponentially since the 1940s, and there are now more than 84,000 different chemicals in commerce.1 While many of these chemicals have allowed for modern conveniences (eg, plastics) or were developed to address safety (eg, flame retardants) and other societal needs (eg, pesticides) to improve our quality of life, recent advances in the fields of exposure science and analytical chemistry have documented widespread exposure to hundreds of these chemicals among men, women, and children throughout the world. Depending on the chemical, exposure can occur through food, drinking water, air, soil, house dust, and direct contact with various household materials or consumer products. Exposures among children are especially of concern because children have contact with potentially contaminated soil and dust; have frequent hand-to-mouth or object-to-mouth activity; eat, drink and breathe more per body weight compared with adults; and undergo many rapid changes that are susceptible to even minute doses of environmental stressors.2 Fetal and infant exposures are also of concern because many chemicals have been shown to pass through the placenta and/or from mother to infant through breast milk.

Numerous high-production-volume chemicals—those produced or imported in the United States in quantities of 1 million pounds or more per year (currently numbering approximately 3000)—are known or suspected endocrine disrupt-
ing chemicals (EDCs). Once inside the body, EDCs can affect the endocrine system through a multitude of specific mechanisms that can target different levels of the hypothalamic-pituitary-gonad, thyroid, and adrenal axes, ranging from effects on hormone receptors to effects on hormone synthesis, secretion, or metabolism; therefore, they can have far-reaching health implications throughout the life course. Transgenerational effects are also possible, as is now being observed in offspring of women who had been exposed to diethylstilbestrol in utero decades ago. The realization that exposure to many environmental EDCs is now ubiquitous, coupled with proven or suggested trends for increased rates of certain endocrine-related diseases and disorders among children, has resulted in growing concern regarding potential links between the two among scientists, governments, physicians, and patients. Several scientific bodies, including the Endocrine Society, now support that EDCs can affect human health. However, human studies investigating possible adverse health effects of EDCs, especially among children, are surprisingly deficient for most EDCs.

This review provides a brief introduction to several common EDCs, an overview of the state of the human evidence for adverse effects of EDCs on child development, guidance for health care providers based on current knowledge, and recommendations for future research. As an overview, it does not provide in-depth information on any of the individual exposures or outcomes introduced and discusses only a small portion of all known or suspected EDCs. Seminal studies, select examples, and previous review articles focusing on various subtopics are referenced here, and the interested reader is directed toward those for additional detail.

**ENDOCRINE DISRUPTING CHEMICALS**

**Persistent Organic Pollutants**

Persistent organic pollutants (POPs) are lipophilic chemicals with long half-lives that bioaccumulate up the food chain and include polychlorinated biphenyls (PCBs), organochlorine pesticides (eg, dichlorodiphenyldichloroethylene [DDT], chlordane, and hexachlorobenzene), polybrominated diphenyl ethers (PBDEs), other brominated flame retardants, and others. The PCBs are a class of chemicals widely used as transformer and hydraulic fluids and as additives in paints, oils, and building materials. Both DDT and other organochlorine pesticides were widely used after World War II and were regarded at the time as safe and effective alternatives to arsenic-based pesticides. In response to reports of high concentrations in the environment owing to their persistence, effects on wildlife, and the potential to harm human health, PCBs and some of the more heavily used organochlorine pesticides were banned in industrialized nations in the 1970s. The use of DDT still occurs in some developing countries as an effective and affordable method to combat malaria and other vector-borne illnesses. The PBDEs and other flame retardants are found in furniture, carpet backing, electronics, and many other consumer products. The use of PBDEs has recently been banned or is currently being phased out in the United States and other countries. Owing to the environmental ubiquity and persistence of POPs, human exposure to them can continue for decades after their use ceases. Continued exposures to PCBs and DDT in countries that have banned their use occur primarily through the diet (dairy, meat, and high-trophic-level fish), although PCB exposure from building materials used in the mid-20th century is also possible. Exposures to PBDEs can occur through the same dietary sources, although exposure to some congeners may occur to a greater extent through contact with house dust after they have leached from products in the home or other indoor environments.

The POPs have been associated with a wide range of adverse health effects in studies of adults, including male and female reproductive problems, thyroid effects, obesity, diabetes, and endocrine-related cancers. Most of this evidence comes from research on PCBs and organochlorine pesticides, although a growing number of studies are now investigating health effects related to PBDE exposures.

**Phthalates**

Phthalates are a diverse class of widely used industrial chemicals. They are used as plasticizers to make plastics more flexible and are also used as solubilizing or stabilizing agents. Phthalates can be found in an extensive array of products. Low-molecular-weight phthalates are found in personal care products, certain dietary supplements and medications, and other consumer goods. High-molecular-weight phthalates are found in flexible polyvinyl chloride commonly found in consumer products, food packaging, home furnishings, and other building materials. Medical equipment can also contain phthalates, and elevated exposures have been documented among infants in the neonatal intensive care unit. Owing to this widespread use, urinary phthalate metabolites can be measured in virtually everyone. Several phthalates are antiandrogenic, and in rodents they have demonstrated significant adverse effects on male reproductive development and numerous other end points at high doses. In human studies of adults, phthalates have been related to decreases in sex steroid and thyroid hormone levels, poor sperm quality, endometriosis, insulin resistance, obesity, and possibly breast cancer.

**Bisphenol A**

Bisphenol A (BPA) is a high-production chemical used in the manufacture of polycarbonate plastics, epoxy resins, and thermal paper. Polycarbonate is a clear, rigid plastic that has been used for water bottles and other items, while epoxy resins are found in the lining of many canned foods and in certain construction materials. As with phthalates, medical equipment may also contain BPA, as infants in the neonatal intensive care unit have been shown to have elevated exposure levels. For most people, exposure to BPA occurs primarily through the diet, and measurable levels of BPA can be found in most people. It has been known to be weakly estrogenic for 75 years, and recent animal studies have reported a diverse variety of developmental problems following early life exposure such
as altered reproductive organ development and neurobehavioral effects. Human studies of BPA remain limited, although in adults there have been suggestive relationships with male and female reproductive end points, altered thyroid hormone levels and liver function, cardiovascular disease, and diabetes.

Contemporary-Use Pesticides

Owing to the long-lasting environmental issues related to the persistent organochlorine pesticides described earlier, nearly all pesticides used today are nonpersistent. While they are designed to break down in a matter of hours or days, it has been shown that many nonpersistent pesticides can remain for years after application in homes and other indoor environments where they are protected from moisture, sunlight, and other degradation mechanisms. Exposure is multimedia, multipathway, and multiroute and can depend on the chemical, scenario, and population. Pesticides are known neurotoxins, especially in high-dose situations. Many commonly used pesticides are also known or suspected EDCs, although studies of potential endocrine effects have greatly lagged behind research focused on their designed mode of action (eg, cholinesterase inhibition). Among all the types of pesticides (insecticides, herbicides, fungicides, rodenticides, etc), most research in humans has been conducted for insecticides. The most common classes of insecticides are organophosphates, carbamates, and pyrethroids. Of these, the organophosphates, some of which have been banned or restricted for residential but not agricultural use in the United States, have been studied the most.

Other Chemicals

There are many other types of known or suspected EDCs for which widespread human exposure has been documented. A large body of evidence shows that a number of heavy metals such as lead, cadmium, and mercury may affect endocrine function in addition to their other modes of toxic effects. There is also a growing list of emerging EDCs of concern, including parabens, triclosan, perchlorate, altered thyroid hormone levels and liver function, cardiovascular disease, and diabetes.

DEVELOPMENTAL END POINTS RELATED TO EDCS

Fetal Growth and Gestation Duration

Low birth weight and preterm birth are the leading causes of infant mortality and precursors to future morbidity, and both have increased significantly in the United States since 1990. Numerous studies have assessed relationships between chemical exposures and birth weight, which have been extensively reviewed. Studies among EDCs are more limited compared with those of agents related to ambient air pollution such as particulate matter, carbon monoxide, ozone, nitrogen dioxide, and sulfur dioxide. There is some inconsistent evidence for reduced birth weight in association with exposure to POPs, organophosphate insecticides, and triazine herbicides. A meta-analysis of nearly 8000 women from 12 European birth cohorts dating back to 1990 reported significant declines in birth weight in relation to markers of low-level exposure to PCBs but not DDT. More recently, evidence for reduced birth weight in relation to phthalates, BPA, and PBDE has been reported, although several studies have reported no associations. Because study designs and results have varied across studies, for most EDCs it is currently difficult to conclude whether a relationship exists between exposure and birth weight.

Few studies have investigated the potential relationship between EDC exposure and preterm birth, and most have focused on PCBs and organochlorine pesticides. Since these exhaustive literature reviews were published, a small nested case-control study (n=60) taking place in Mexico City, Mexico, reported higher concentrations of phthalates and BPA in third-trimester urine of women who delivered preterm compared with women who delivered at term. For phthalates, this was consistent with 2 studies reporting inverse relationships between phthalates and gestation duration. On the other hand, 2 studies have reported null or even positive associations between phthalates and gestation duration. Future studies are needed on the relationship between EDCs and preterm birth and should account for the heterogeneous etiologies of preterm birth to enhance study precision.

Male Reproductive Tract Development

There is evidence that birth anomalies of the male reproductive tract (cryptorchidism, hypospadias) may have increased in some countries in recent decades. A leading hypothesis for a collection of linked conditions in human males exposed to EDCs in utero is termed testicular dysgenesis syndrome. Testicular dysgenesis syndrome represents a number of reproductive disorders of varying severity that are associated with disturbed gonadal development including cryptorchidism, hypospadias, and smaller reproductive organs. Later in life, the effects of testicular dysgenesis syndrome are hypothesized to manifest as a reduction in semen quality and infertility as well as an increased risk of testicular cancer. The evidence for widespread endocrine disruption among males is thus further fueled by reports of significant secular declines in semen quality and testosterone as well as increased rates of testicular cancer in men during the past 50 years or so. Several studies have assessed relationships between EDCs, particularly POPs, and male genital birth defects, with inconsistent findings that have been reviewed previously. More recently, a large case-control study (471 cases and 490 control subjects) of maternal occupation reported a significantly increased risk of hypospadias associated with exposure to hairspray and phthalates, some of which are antiandrogenic.
other recent case-control study reported an increased risk of hypospadias and cryptorchidism in relation to parental occupational exposure to pesticides, although the number of cases in the study was relatively small (14 with hypospadias, 18 with cryptorchidism). A relationship between PBDE measured in breast milk, but not placenta, and the risk of cryptorchidism was also reported in a Danish case-control study of 95 boys with cryptorchidism.37

More subtle measures of reproductive tract development have been studied in relation to EDCs in recent years. A landmark US study reported reduced anogenital distance (a marker for insufficient fetal androgenization), penis size, and incomplete testicular descent in 106 boys aged 2 to 24 months in relation to several urinary phthalate metabolites measured in third-trimester maternal urine. A newer Japanese study that measured phthalate metabolites in 111 pregnant women also reported inverse associations with anogenital distance in male infants.39 Finally, a Danish study reported significant decreases in serum measures of free testosterone and Leydig cell function in 3-month-old boys in relation to phthalates in maternal breast milk.40 Thus, there is evidence that phthalates and possibly other EDCs disrupt early male reproductivity development, but additional studies are needed.

Pubertal Development

A secular decline in the age at onset of puberty and an increased frequency of precocious puberty have been observed during the past couple decades in the United States and other countries. These trends are considered to be a significant public health concern because precocious puberty is a risk factor for endocrine-related diseases in adulthood. The trends cannot be fully explained by known predictors (eg, living conditions, body mass index [BMI; calculated as weight in kilograms divided by height in meters squared]), and exposure to EDCs has been hypothesized to be a significant contributor. Several studies have reported an association between exposure to POPs and precocious puberty or earlier menarche in girls and delayed puberty in boys; however, a number of studies have not observed these relationships.

There has been a lack of research on nonpersistent EDCs and pubertal development. Levels of several phthalates were found to be elevated in serum of girls with premature thelarche compared with control subjects in a small study in Puerto Rico. However, the study has been criticized on several aspects of the study design, including the potential for sample contamination when measuring phthalate levels in serum. A more recent US study of pubertal development among 1151 girls aged 6 to 8 years at enrollment reported subtle but statistically suggestive positive associations between urinary low-molecular-weight phthalate metabolites and breast and pubic hair development. The authors also reported a weak inverse relationship between high-molecular-weight phthalate levels and pubic hair stage but no associations between BPA levels and pubertal development. Among boys, a small study conducted in Turkey reported that plasma concentrations of high-molecular-weight phthalates were significantly higher in 11- to 15-year-olds with pubertal gynecomastia compared with a control group.48 Additional studies on EDC exposure and pubertal development are greatly needed owing to the current lack of human data.

Neurodevelopment

Neurodevelopmental disorders are prevalent in the United States and worldwide, with evidence that rates of certain disorders such as attention-deficit/hyperactivity disorder and autism spectrum disorders have been increasing in recent years. While it is likely that these trends are attributable to numerous factors including changes in diagnostic practices, there is growing evidence that exposure to EDCs may play a significant role. Sex steroid hormones are vital to central nervous system development. Thus, developing neuroendocrine systems may be particularly sensitive to EDC exposure. Longitudinal and/or cross-sectional human studies have related exposure to EDCs, both in utero and during early childhood, with neurodevelopmental disorders such as decreased IQ, poorer memory, autism spectrum disorders, attention-deficit/hyperactivity disorder, and other behavioral problems. These data are most robust for PCBs and pesticides. However, there is recent evidence that certain phthalates may be associated with each of these end points, as well as reduced masculine play in boys, that gestational BPA exposure may be associated with poorer executive function and behavior in 3-year-old girls, and that gestational exposure to PBDEs could be related to lower scores on tests of mental development in the first few years of life.

Thyroid hormones also play an essential role in neurodevelopment in addition to many other functions related to growth and metabolism. Rates of thyroid dysfunction, including congenital hypothyroidism, have been on the rise during the past several decades. There is a growing list of EDCs that have been found capable of disrupting thyroid function. Both human and animal studies suggest that PCBs, PBDEs, pesticides, phthalates, BPA, and numerous other EDCs may disrupt thyroid signaling through diverse mechanisms. More research is needed to establish dose-response relationships between EDCs and adverse neurodevelopment as well as to determine the most sensitive stages and precise biological mechanisms involved.

Obesity

The prevalence of overweight and obesity is rapidly increasing in the United States and worldwide. In addition to diet, physical activity, and genetics, environmental "obesogens" may play a role in these trends. Obesogens are defined as chemicals that inappropriately alter lipid homeostasis to promote adipogenesis and lipid accumulation, and experimental evidence showing that numerous chemicals may impart these effects is growing. Human studies of environmental exposures in relation to obesity among children are lacking. They are primarily limited to studies of POPs, and results have been
inconsistent.54,66 Cord blood PCB and dichlorodiphenyl-
dichloroethylenne (a persistent lipophilic metabolite of
DDT) concentrations were associated with increased BMI
or change in BMI from ages 1 to 3 years in a Belgian pro-
spective study.67 In a cross-sectional study of adoles-
cents, 3 serum PCB congeners (138, 153, and 180) were
associated with decreased BMI but a fourth (118) was posi-
tively associated with BMI among 14- to 15-year-
olds.68 Several studies have reported null results as well.64
For nonpersistent EDCs, research has been limited to 2
cross-sectional studies that have reported suggestive posi-
tive associations between certain phthalates and BMI in
girls.66,69 More research is needed to more adequately as-
ss whether EDC exposure is associated with child-
hood obesity and related conditions (metabolic syn-
drome, diabetes, and future cardiovascular disease).

CLINICAL PERSPECTIVES

Based on the available data, it is currently impossible to
determine individual-level risk and whether there are safe
levels of exposure to EDCs. Although the effect esti-
mates or expected changes in developmental markers re-
ported in individual studies may seem subtle, a seem-
ingly small shift in the population distribution for these
measures in relation to exposure is of great public health
concern because exposure is ubiquitous. Given the range
of potential serious developmental effects described here,
efforts to reduce EDC exposure as a precaution among
pregnant women and children are warranted. The first
level of concern is for those highly exposed, and physi-
cians should obtain occupational and environmental ex-
posure history information. Occupational exposure his-
tory for the parents may shed light on potentially
important in utero exposures. Current "take-home" ex-
posure may also occur for some children, wherein the
parent's clothing or other articles contaminated from the
workplace can lead to exposures in the home or car. Pa-
tient or parent accounts of product overuse, hobbies,
home-based businesses, or contaminated locations where
children spend time are some examples of potentially use-
ful environmental history information.70

Because exposure to the chemicals described here oc-
curs among virtually everyone as they go about their nor-
mal activities, all patients could be advised to take cer-
tain steps in an attempt to reduce exposure. They can
purchase consumer goods or personal care products la-
beled "phthalate free" or "BPA free," which are becom-
ing more commonly available. However, this trend has
been primarily due to marketing purposes, and prod-
ucts containing these chemicals are generally not re-
quired to be labeled as such.71 For BPA and high-
molecular-weight phthalates, replacing foods in the diet
that involve plastic food packaging with fresh alterna-
tives may reduce exposure by more than 50%.72 Among
fresh foods, replacing a diet of conventional produce with
organic produce may significantly reduce exposure to or-
ganoephosphate pesticides for children who are exposed
primarily through residues in food.73 For legacy POPs like
PCBs and DDT that are no longer used in most coun-
tries as well as for more contemporary POPs such as
PBDEs, consuming a diet lower in animal fats may
reduce exposure. Individuals who live near polluted
waters should also adhere to local fishing advisories. Be-
cause homes, offices, daycares, and cars still have many
products that contain PBDEs and because other flame re-
tardants are being used in new products, careful product
selection and cleaning practices to reduce indoor dust ex-
posure (eg, cleaning carpets and dusty surfaces regularly,
using a vacuum cleaner with a high-efficiency particulate
air filter) may help reduce exposure.74

Health care providers are encouraged to practice pri-
mary prevention by learning about EDC exposure sources
and potential health effects. Several resources are avail-
ble for health care professionals and patients, includ-
ing handouts designed by university-based Pediatric En-
vironmental Health Specialty Units (http://www.aoe-
c.org/PEHSU/facts.html), a pediatric environmental health
toolkit from Physicians for Social Responsibility (http:
//www.psr.org/resources/pediatric-toolkit.html), the
"green book": Pediatric Environmental Health from the
American Academy of Pediatrics (http://ebooks.aap.org
/product/pediatric-environmental-health-3rd-edition), and
guidance on collecting pediatric exposure history from
the National Environmental Education Foundation
(http://www.neefusa.org/health/PEII/index.htm).16 Hos-
pitals may help prevent exposures among sensitive popu-
lations through their purchasing practices such as seek-
ing out polyvinyl chloride–free products for use in the
neonatal intensive care unit.75 Finally, clinicians are en-
couraged to consult with physicians or other profession-
als trained in environmental and occupational health as
needed to address specific exposures or potential envi-
ronment-related health conditions. A resource for cli-

cian referrals is the Pediatric Environmental Health Spe-

cialty Units network of pediatric environmental health
care providers (http://www.aoeq.org/pehsu.htm).

REGULATORY PERSPECTIVES

While the steps listed here may help reduce exposure to
some extent, exposure to most EDCs is multisource, mul-
tipathway, and multiroute. Individual exposure sce-
narios depend on many factors, many of which are not
modifiable through personal choices and activities. Thus,
the most effective way to reduce risk is at the regulatory
level. The regulatory framework for controlling chemi-
cal risks in the United States is considered outdated and
ineffective.76 An extremely small proportion of chemi-
cals in current use have been thoroughly tested for en-
docrine disrupting potential, and there has been little mo-
tivation for chemical producers to assess this during
product development and registration. In 1996, the US
Environmental Protection Agency enacted legislation re-
quiring that special considerations be given to child sus-
ceptibility in the risk assessment of pesticides but not other
industrial or consumer chemicals. The 1996 legislation
also mandated that pesticides and certain drinking wa-
ter contaminants be screened for endocrine disrupting
activity, which resulted in implementation of the Envi-
ronmental Protection Agency Endocrine Disrupting
Screening Program.77 In 2009, the Environmental Pro-
tection Agency finally ordered producers to conduct the
first set of endocrine screening tests for a truncated list

ARCH PEDIATR ADOLESC MED/VOL 166 (NO. 10), OCT 2012 WWW.ARCHPEDIATRICS.COM
of chemicals, but at the time this article was written, data from these new tests were still not available. In addition to data on health risks, data on exposure sources and pathways are also needed to inform the most effective and cost-efficient regulations. For example, several phthalates have been banned from use in children’s toys in the United States. However, the most sensitive exposure period may be in the developing fetus, and this would likely not be reduced with legislation geared only toward children’s toys. Finally, there must be caution when replacing chemicals deemed high risk with new chemicals for which we know less about the potential toxic effects.

CONCLUSIONS AND FUTURE RESEARCH NEEDS

A growing body of evidence shows that exposure to a number of chemicals may adversely affect child development through altered endocrine function. However, many of the potential exposure-response relationships described here have not been adequately explored. For those that have been investigated in multiple studies, results have been inconsistent across studies. There are many possible explanations for variability in study findings, including differences in sample size, study design, study populations, life stage, data analysis approaches, and strategies for obtaining data on exposures, end points, and important covariates. Many studies on EDCs to date among both children and adults are cross-sectional; there is a great need for well-designed longitudinal studies that measure both exposure and developmental end points at multiple potentially sensitive times. For nonpersistent EDCs, it is especially important for studies to consider intraindividual variability in exposure levels over time. Future research aimed at explaining sexually dimorphic effects of EDCs on development is also needed, as are studies capable of exploring health effects resulting from exposure to multiple EDCs simultaneously to more closely reflect the reality of being exposed to chemical mixtures. Research that combines molecular epidemiology and toxicology approaches should be conducted to establish causality and to elucidate specific biological mechanisms of EDCs in humans, individual susceptibility factors, and the stages of development most sensitive to exposure. Finally, more research is needed in the area of exposure science to enable more precise effect estimates in epidemiology studies used for risk assessment as well as to provide solid data on important exposure sources and pathways for risk management. The National Children’s Study (http://www.nationalchildrenssstudy.gov) and the Centers for Children’s Environmental Health and Disease Prevention Research (http://www.niehs.nih.gov/research/supported/centers/prevention/) are important sources of cutting-edge research for developing new information on these topics.

Accepted for Publication: February 21, 2012.
Published Online: June 4, 2012. doi:10.1001/archpediatrics.2012.241
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Financial Disclosure: None reported.
Funding/Support: This work was supported by grants R01ES018872, P42ES017198, P02ES018171, and P30ES017885 from the National Institute of Environmental Health Sciences and RD3480001 from the US Environmental Protection Agency.
Disclaimer: The content is solely the responsibility of the author and does not necessarily represent the official views of the National Institute of Environmental Health Sciences or the US Environmental Protection Agency.

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