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Contents

Thrice Monthly Volume 10 Number 31 November 6, 2022

REVIEW

- 11214 Diabetes and skin cancers: Risk factors, molecular mechanisms and impact on prognosis
Dobrică EC, Banciu ML, Kipkorir V, Khazeei Tabari MA, Cox MJ, Simhachalam Kutikuppala LV, Găman MA
- 11226 Endocrine disruptor chemicals as obesogen and diabetogen: Clinical and mechanistic evidence
Kurşunoğlu NE, Sarer Yurekli BP
- 11240 Intestinal microbiota in the treatment of metabolically associated fatty liver disease
Wang JS, Liu JC

MINIREVIEWS

- 11252 Lactation mastitis: Promising alternative indicators for early diagnosis
Huang Q, Zheng XM, Zhang ML, Ning P, Wu MJ
- 11260 Clinical challenges of glycemic control in the intensive care unit: A narrative review
Sreedharan R, Martini A, Das G, Aftab N, Khanna S, Ruetzler K
- 11273 Concise review on short bowel syndrome: Etiology, pathophysiology, and management
Lakkasani S, Seth D, Khokhar I, Touza M, Dacosta TJ
- 11283 Role of nickel-regulated small RNA in modulation of *Helicobacter pylori* virulence factors
Freire de Melo F, Marques HS, Fellipe Bueno Lemos F, Silva Luz M, Rocha Pinheiro SL, de Carvalho LS, Souza CL, Oliveira MV
- 11292 Surgical intervention for acute pancreatitis in the COVID-19 era
Su YJ, Chen TH

ORIGINAL ARTICLE

Clinical and Translational Research

- 11299 Screening of traditional Chinese medicine monomers as ribonucleotide reductase M2 inhibitors for tumor treatment
Qin YY, Feng S, Zhang XD, Peng B

Case Control Study

- 11313 Covered transjugular intrahepatic portosystemic stent-shunt *vs* large volume paracentesis in patients with cirrhosis: A real-world propensity score-matched study
Dhaliwal A, Merhzad H, Karkhanis S, Tripathi D

Retrospective Cohort Study

- 11325** Endoscopic submucosal tunnel dissection for early esophageal squamous cell carcinoma in patients with cirrhosis: A propensity score analysis
Zhu LL, Liu LX, Wu JC, Gan T, Yang JL

Retrospective Study

- 11338** Nomogram for predicting overall survival in Chinese triple-negative breast cancer patients after surgery
Lin WX, Xie YN, Chen YK, Cai JH, Zou J, Zheng JH, Liu YY, Li ZY, Chen YX
- 11349** Early patellar tendon rupture after total knee arthroplasty: A direct repair method
Li TJ, Sun JY, Du YQ, Shen JM, Zhang BH, Zhou YG
- 11358** Coxsackievirus A6 was the most common enterovirus serotype causing hand, foot, and mouth disease in Shiyan City, central China
Li JF, Zhang CJ, Li YW, Li C, Zhang SC, Wang SS, Jiang Y, Luo XB, Liao XJ, Wu SX, Lin L
- 11371** Dynamic changes of estimated glomerular filtration rate are conversely related to triglyceride in non-overweight patients
Liu SQ, Zhang XJ, Xue Y, Huang R, Wang J, Wu C, He YS, Pan YR, Liu LG
- 11381** C-reactive protein as a non-linear predictor of prolonged length of intensive care unit stay after gastrointestinal cancer surgery
Yan YM, Gao J, Jin PL, Lu JJ, Yu ZH, Hu Y

Clinical Trials Study

- 11391** Dan Bai Xiao Formula combined with glucocorticoids and cyclophosphamide for pediatric lupus nephritis: A pilot prospective study
Cao TT, Chen L, Zhen XF, Zhao GJ, Zhang HF, Hu Y

Observational Study

- 11403** Relationship between lipids and sleep apnea: Mendelian randomization analysis
Zhang LP, Zhang XX
- 11411** Efficacy and safety profile of two-dose SARS-CoV-2 vaccines in cancer patients: An observational study in China
Cai SW, Chen JY, Wan R, Pan DJ, Yang WL, Zhou RG

Prospective Study

- 11419** Pressure changes in tapered and cylindrical shaped cuff after extension of head and neck: A randomized controlled trial
Seol G, Jin J, Oh J, Byun SH, Jeon Y

Randomized Controlled Trial

- 11427** Effect of intradermal needle therapy at combined acupoints on patients' gastrointestinal function following surgery for gastrointestinal tumors
Guo M, Wang M, Chen LL, Wei FJ, Li JE, Lu QX, Zhang L, Yang HX

SYSTEMATIC REVIEWS

- 11442** Video-assisted bystander cardiopulmonary resuscitation improves the quality of chest compressions during simulated cardiac arrests: A systemic review and meta-analysis
Pan DF, Li ZJ, Ji XZ, Yang LT, Liang PF

META-ANALYSIS

- 11454** Efficacy of the femoral neck system in femoral neck fracture treatment in adults: A systematic review and meta-analysis
Wu ZF, Luo ZH, Hu LC, Luo YW
- 11466** Prevalence of polymyxin-induced nephrotoxicity and its predictors in critically ill adult patients: A meta-analysis
Wang JL, Xiang BX, Song XL, Que RM, Zuo XC, Xie YL

CASE REPORT

- 11486** Novel compound heterozygous variants in the LHX3 gene caused combined pituitary hormone deficiency: A case report
Lin SZ, Ma QJ, Pang QM, Chen QD, Wang WQ, Li JY, Zhang SL
- 11493** Fatal bleeding due to an aorto-esophageal fistula: A case report and literature review
Ćeranić D, Nikolić S, Lučev J, Slanić A, Bujas T, Ocepek A, Skok P
- 11500** Tolvaptan ameliorated kidney function for one elderly autosomal dominant polycystic kidney disease patient: A case report
Zhou L, Tian Y, Ma L, Li WG
- 11508** Extensive right coronary artery thrombosis in a patient with COVID-19: A case report
Dall'Orto CC, Lopes RPF, Cancela MT, de Sales Padilha C, Pinto Filho GV, da Silva MR
- 11517** Yokoyama procedure for a woman with heavy eye syndrome who underwent multiple recession-resection operations: A case report
Yao Z, Jiang WL, Yang X
- 11523** Rectal cancer combined with abdominal tuberculosis: A case report
Liu PG, Chen XF, Feng PF
- 11529** Malignant obstruction in the ileocecal region treated by self-expandable stent placement under the fluoroscopic guidance: A case report
Wu Y, Li X, Xiong F, Bao WD, Dai YZ, Yue LJ, Liu Y
- 11536** Granulocytic sarcoma with long spinal cord compression: A case report
Shao YD, Wang XH, Sun L, Cui XG
- 11542** Aortic dissection with epileptic seizure: A case report
Zheng B, Huang XQ, Chen Z, Wang J, Gu GF, Luo XJ

- 11549** Multiple bilateral and symmetric C1-2 ganglioneuromas: A case report
Wang S, Ma JX, Zheng L, Sun ST, Xiang LB, Chen Y
- 11555** Acute myocardial infarction due to Kounis syndrome: A case report
Xu GZ, Wang G
- 11561** Surgical excision of a large retroperitoneal lymphangioma: A case report
Park JH, Lee D, Maeng YH, Chang WB
- 11567** Mass-like extragonadal endometriosis associated malignant transformation in the pelvis: A rare case report
Chen P, Deng Y, Wang QQ, Xu HW
- 11574** Gastric ulcer treated using an elastic traction ring combined with clip: A case report
Pang F, Song YJ, Sikong YH, Zhang AJ, Zuo XL, Li RY
- 11579** Novel liver vein deprivation technique that promotes increased residual liver volume (with video): A case report
Wu G, Jiang JP, Cheng DH, Yang C, Liao DX, Liao YB, Lau WY, Zhang Y
- 11585** Linear porokeratosis of the foot with dermoscopic manifestations: A case report
Yang J, Du YQ, Fang XY, Li B, Xi ZQ, Feng WL
- 11590** Primary hepatic angiosarcoma: A case report
Wang J, Sun LT
- 11597** Hemorrhagic shock due to ruptured lower limb vascular malformation in a neurofibromatosis type 1 patient: A case report
Shen LP, Jin G, Zhu RT, Jiang HT
- 11607** Gastric linitis plastica with autoimmune pancreatitis diagnosed by an endoscopic ultrasonography-guided fine-needle biopsy: A case report
Sato R, Matsumoto K, Kanzaki H, Matsumi A, Miyamoto K, Morimoto K, Terasawa H, Fujii Y, Yamazaki T, Uchida D, Tsutsumi K, Horiguchi S, Kato H
- 11617** Favorable response of primary pulmonary lymphoepithelioma-like carcinoma to sintilimab combined with chemotherapy: A case report
Zeng SY, Yuan J, Lv M
- 11625** Benign paroxysmal positional vertigo with congenital nystagmus: A case report
Li GF, Wang YT, Lu XG, Liu M, Liu CB, Wang CH
- 11630** Secondary craniofacial necrotizing fasciitis from a distant septic emboli: A case report
Lee DW, Kwak SH, Choi HJ
- 11638** Pancreatic paraganglioma with multiple lymph node metastases found by spectral computed tomography: A case report and review of the literature
Li T, Yi RQ, Xie G, Wang DN, Ren YT, Li K

- 11646** Apnea caused by retrobulbar anesthesia: A case report
Wang YL, Lan GR, Zou X, Wang EQ, Dai RP, Chen YX
- 11652** Unexplained septic shock after colonoscopy with polyethylene glycol preparation in a young adult: A case report
Song JJ, Wu CJ, Dong YY, Ma C, Gu Q
- 11658** Metachronous isolated penile metastasis from sigmoid colon adenocarcinoma: A case report
Yin GL, Zhu JB, Fu CL, Ding RL, Zhang JM, Lin Q

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Endocrine disruptor chemicals as obesogen and diabetogen: Clinical and mechanistic evidence

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Abstract

Obesity is becoming an inevitable pandemic all over the world. The World Obesity Federation predicts in the 2022 World Obesity Atlas that one billion people worldwide, including 1 in 5 women and 1 in 7 men, will be living with obesity by 2030. Moreover, the prevalence of diabetes is increasing worldwide, and diabetes is becoming more of a public health problem. Increased insulin resistance due to obesity and deficiency in insulin secretion are the two main causes of type 2 diabetes mellitus (T2DM). An exogenous chemical or mixture of chemicals that interferes with any aspect of hormone action was defined as endocrine-disrupting chemicals (EDCs). Bisphenol A (BPA), the first known EDC, was synthesized and was considered to be estrogenic. Global production of BPA has increased progressively from 5 to 8 million tons (MT) between 2010 and 2016. Furthermore, researchers estimated that the production should reach 10.2 MT by 2022. The human population is exposed to EDCs in daily life in such forms as pesticides/herbicides, industrial and household products, plastics, detergents, and personal care products. The term obesogen was used for chemicals that promote weight gain and obesity by increasing the number of adipocytes and fat storage in existing adipocytes, changing the energy balance, and finally regulating appetite and satiety. Besides the obesogenic effect, EDCs can cause T2DM through alteration in β cell function and morphology and insulin resistance. In this review, we provide clinical and mechanistic evidence regarding EDCs as obesogen and diabetogen. However, those studies are not enough methodologically to indicate causality. In this respect, randomized clinical trials are needed to investigate the association between obesogen, diabetogen and the related metabolic clinical picture.

Key Words: Endocrine disruptors; Adipogenesis; Obesity; Diabetes mellitus

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Core Tip: An exogenous chemical, or mixture of chemicals, that interferes with any aspect of hormone action was defined as Endocrine-Disrupting Chemicals (EDCs). Obesogens can promote obesity by increasing the number of adipocytes and fat storage in existing adipocytes, changing the calories burned at rest, changing the energy balance, and finally regulating satiety. Besides the obesogenic effect, EDCs can cause type 2 diabetes mellitus through alteration in β cell function and morphology and insulin resistance. In this review, we provide clinical and mechanistic evidence regarding EDCs as obesogen and diabetogen.

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INTRODUCTION

Obesity has become a “preventable” pandemic affecting people of all ages around the world. Globally, obesity has nearly tripled since 1975. In 2016, 39% of adults (more than 1.9 billion) aged 18 and over were overweight and 13% (more than 650 million) were obese[1]. The World Obesity Federation predicts in the 2022 World Obesity Atlas that one billion people worldwide, including 1 in 5 women and 1 in 7 men, will be living with obesity by 2030[2]. The International Classification of Disease defines obesity as a chronic, recurrent, and multifactorial disease[3]. It is also a significant risk factor for several other non-communicable diseases (NCDs), such as metabolic diseases [*e.g.*, type 2 diabetes mellitus (T2DM) and fatty liver], cardiovascular diseases (such as hypertension, myocardial infarction, and stroke), and some malignancies (including breast, ovarian, prostate, liver, kidney, and colorectal cancers)[4]. Obesity affects the mind and body in many ways, including hunger, satiety, metabolism, hormone balance, and body weight. These changes can remain the same for many years, even if the weight is lost. In addition, obesity is a disease that recurs frequently. This means that individuals are treated without changing the obesogenic environment and other underlying causes, and then individuals are re-exposed to the same environment[2].

Diabetes is a progressive chronic disease that occurs when the pancreas cannot produce enough insulin, or the body cannot use the produced insulin effectively. The prevalence of diabetes is increasing worldwide, and diabetes is becoming more of a public health problem.

In 2021, an estimated 537 million adults worldwide were living with diabetes[5], up from 108 million in 1980[6]. The global prevalence of diabetes has more than doubled since 1980, from 4.7% to 10.5%. In the 10th edition of the Diabetes Atlas published by the International Diabetes Federation, it is estimated that 643 million adults will be living with diabetes by 2030, and 783 million adults by 2045[5]. In addition, total health expenditures related to diabetes are projected to be \$966 billion, \$1028 billion, and \$1054 billion in those years, respectively. Another feature of these expenditures is that the prevalence of diabetes has been increasing rapidly over the past three decades, with this increase being even faster in low- and middle-income countries.

Diabetes is treatable and its consequences can be avoided or prevented by diet, physical activity, medications, and regular check-ups. However, diabetes is still a major cause of blindness, kidney failure, lower limb amputation, and many other conditions that affect the quality of life in the long term [7].

ENDOCRINE DISRUPTORS

Endocrine disruptors were defined as, “an exogenous chemical, or mixture of chemicals, that interferes with any aspect of hormone action”, in The Endocrine Society's Second Scientific Statement on endocrine-disrupting chemicals (EDCs)[8]. The history of EDCs goes back a long time. The first known EDC, Bisphenol A (BPA), was synthesized in 1891 and was considered to be estrogenic in 1936[9]. However, we must keep in mind that by definition there can be hundreds of other EDCs.

Persistent organic pollutants

Persistent organic pollutants (POPs) are a group of chemicals that include pesticides (DDT, HCB) and industrial chemicals, for instance, polychlorinated bisphenols (PCBs) (Figure 1). POPs bioaccumulate in tissues and amplify up the food chain[10]. POPs persist in the environment for long periods because they are chemically resistant to environmental degradation. They can accumulate and pass from one species to the next through the food chain[11]. Three kinds of POPs named chlorinated, hydrophobic, and brominated accumulate predominantly in adipose-rich tissues[12].

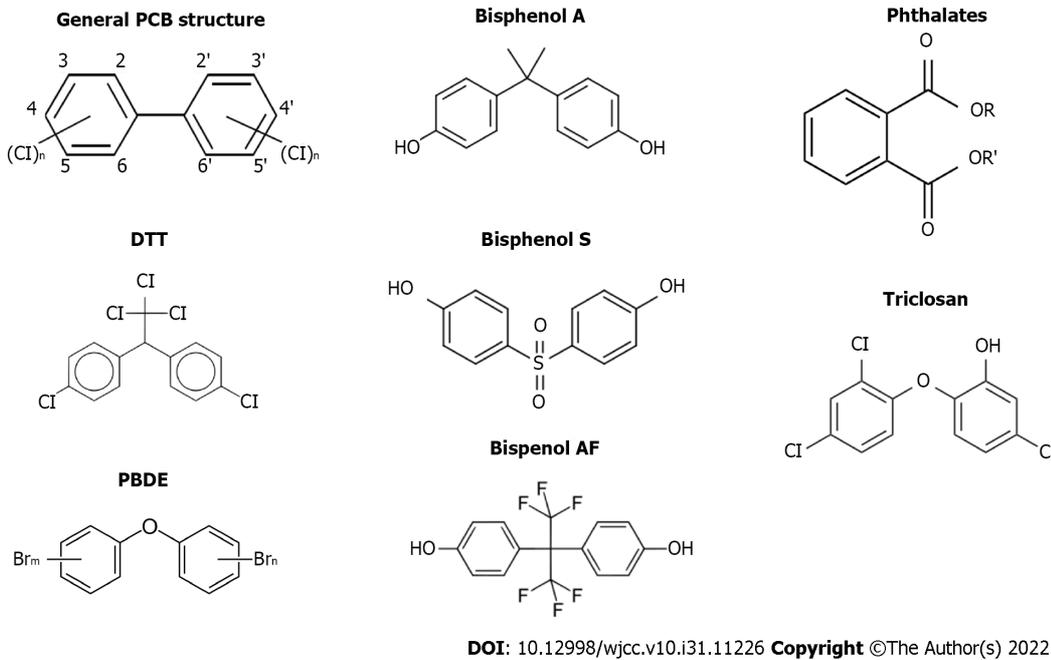


Figure 1 General chemical structure of endocrine disruptors. PCB: Polychlorinated bisphenol; PBDE: Polybrominated diphenyl ether.

In addition, adipose tissue plays an important role in POP's storage and toxicokinetics. Adipose tissue stores these chemicals and acts as a buffer. On the other hand, it is a source of constant internal exposure[13]. Although the use of many POPs, especially PCBs, HCB and DDT, is prohibited in most countries, exposure still exists due to their persistence in the environment[14-16].

Heavy metals

Heavy metals are directly related to many cancers. Besides this, two heavy metals, arsenic, and cadmium, are also classified as EDC.

Cadmium

Mining, metallurgy, electroplating, paints, combustion fumes, and overuse of fertilizers and pesticides are the main sources of cadmium contamination[17]. As it is more mobile and soluble compared to other metals, it is quickly absorbed by plants and accumulated in their edible parts[18,19]. Cadmium began to attract attention as an EDC with the discovery of the ability of cadmium and other heavy metals to activate the estrogen receptor[20]. Initially, it was discovered that cadmium binds with high affinity to purified ER α cells and activates them[21].

Arsenic

Inorganic arsenic (iAs) is found naturally in soil and in ground and surface water. This exposure can vary by location and diet. So, exposure to detrimental levels can be widespread[22]. Although multiple mechanisms, including DNA damage and oxidative stress, influence toxicity, there is also some evidence pointing to the interaction of arsenic with steroid receptors[23-25]. In a broader context, these studies provide new evidence that iAs exposure targets many receptors and have many effects that can be considered as an EDC[26,27].

Other "non-persistent" phenolic compounds

Non-persistent endocrine disrupting chemicals refers to a wide variety of chemical compounds used in industrial applications whose main characteristic is a shorter half-life and lower lipid solubility. Nevertheless, with constant exposure, they are continually present in biological samples of the general population[28]. They are commonly encountered in plastics, medical devices, cosmetics, and detergents [29]. Although there are members of this group such as paraben triclosan and phthalates, the most well-known member is BPA.

BPA

In 1891, the first known EDC, BPA, was synthesized and was considered to be estrogenic in 1936 (Figure 1)[9]. Global production of BPA has increased progressively from 5 to 8 million tons (MT) between 2010 and 2016 and is estimated to reach 10.2 MT by 2022[30,31]. Most of the BPA produced is used to produce polycarbonates and epoxy resins[32,33]. However, it is readily found in air[34], soil

[35], water[36], food[37], and in living organisms (humans[36], wildlife[33], and aquatic organisms[38]). In humans, BPA exposure occurs mainly through inhalation, ingestion, and dermal absorption[39]. The presence of BPA in toys, food packaging, and its resin in the lining of conserved food and beverages, to which virtually everyone is constantly exposed[40], facilitates exposure. In food contact materials, BPA may leach into food or water when exposed to high heat, repeated use, or physical manipulation. Studies on BPA have shown that BPA induces weight gain in mice and a high risk of T2DM[28]. Another study conducted in mice showed us that long-term BPA exposure plays a role in the development of glucose tolerance and decreased insulin secretion[41-43]. On the other hand, in humans, prenatal exposure has been shown to be associated with an increase in body fat by age 7 and an increase in body mass index by age 9[44]. These studies show us how closely BPA is related to diabetes and obesity.

BPA substitutes

As mentioned in the forthcoming sections, when various countries restricted or banned the use of BPA, BPA substitutes [*e.g.*, bisphenol S (BPS) and bisphenol F (BPF) and bisphenol AF (BPAF)] began to be used instead of BPA (Figure 1). However, some later studies have revealed that these substitutes also present hormonal activity[45,46]. And these analogues are increasingly being detected in human urine [47,48]. The products labeled as “BPA free” use BPA analogues[46]. This situation also enlarges the risk of exposure to these chemicals in the intrauterine period or in infancy.

Phthalates

Phthalates are a group of chemicals used as liquid plasticizers to increase the elasticity of plastic products (Figure 1). Medical devices, including parenteral feeding tubes, personal care products such as nail polish and perfume, food packaging, and toys contain various phthalates[49]. Unfortunately, phthalates are poorly bio-degradable and highly bioaccumulative in the food chain[50]. It was found that the highest exposure comes from foods that absorb the compound from their packaging or during the production process[28]. Tordjman *et al*[51], notes that phthalates can accumulate in fatty foods such as mayonnaise, dairy products, fatty meat and fish, as well as shellfish, as they have a high solubility in fat. High phthalate exposure has been linked with increased threat of obesity and infertility, increased body mass index (BMI) and waist circumference, insulin resistance, and a change in thyroid hormones [49,52]. Many epidemiological studies have been conducted, especially on body weight and obesity. Although many of these studies have found an association between phthalates, obesity, and weight gain [53-55], some studies have not found a significant association[56]. On the contrary, a few studies have reported a negative correlation[57]. The correlation between phthalate exposure and obesity is, obviously controversial. It should be emphasized that most studies are cross-sectional. Therefore, large prospective studies are needed that would confirm or invalidate the existence of this association.

Triclosan

Triclosan is an extensively used antibacterial agent generally found in antibacterial soaps, toothpaste, oral rinses, toothbrushes, cutting boards, detergents, and plastics in furniture, toys, and sporting goods (Figure 1)[28,58]. Since Triclosan (TCS) can be mixed into nature from domestic wastewater, water and food can also be considered as exposure routes[59]. After ingestion, TCS can be noticed in the blood, plasma, milk, urine, brain, liver, and adipose tissue[60]. In the Weatherly and Gosse’s study[61], it was noted that TSC reduces the total level of T3[62], increases the risk of spontaneous abortion[63], reduces fertility[64], and lowers BMI[65]. Although this and many similar studies consider TCS to be a substance that threatens human health, another group has not been able to determine a correlation that would require TCS to be classified as EDC.

Polybrominated diphenyl ethers

Polybrominated diphenyl ethers (PBDEs), commonly used in upholstered furniture, car seats, cushions, carpet padding and clothing, are mainly used as flame retardants (Figure 1)[44]. Humans may be exposed to polybrominated diphenyl ethers through consumption of foods such as fatty fish, consumption of contaminated water or soil, and inhalation of air containing polybrominated diphenyl ethers[66]. Due to their highly lipophilic structure, PBDEs tend to accumulate in adipose tissue and these chemicals can be released into the blood, especially during weight loss[8]. Many studies show that PBDEs are associated with metabolic syndrome and obesity[67,68]. In addition, insulin resistance in obese individuals has also been associated with the accumulation of PBDEs in adipose tissue[69]. After the phasing out of pentobromine diphenyl ethers in the United States and their prohibition in the European Union[70,71], alternative PBDEs were used in new furniture. However, it is suspected that these compounds may also affect hormonal activities[72,73].

OBESOGEN HYPOTHESIS

The term obesogen was coined for chemicals that promote weight gain and obesity. Obesogens can promote obesity by increasing the number of adipocytes and fat storage in existing adipocytes, changing the calories burned at rest, changing the energy balance, and finally regulating appetite and satiety. In other words, obesogens can cause the development of obesity in a person's later life by modifying the "set point". It can be said that the main mechanism of the effects of obesogen exposure in later life during development is epigenetic changes. The individual's unique epigenetic system determines how the individual's hormonal regulatory system works. These decisions are, of course, directly related to hormonal processes such as appetite and weight gain. Epigenetic regulation of gene expression involves methylation of the CpG islands[74], probably in the gene promoter region, leading to repression of gene expression, and covalent modification of the tails of histone proteins that package DNA[75].

These modifications that occur during the development of the tissue are involved in the differentiation of the tissue during cell division, especially during mitosis. Although generally stable, environmental chemicals and changes in diet can lead to changes in the epigenetic marks, especially during development[8,75]. In conclusion, the obesity hypothesis makes two important points. The first is that the susceptibility to obesity begins during the development of the individual, both intrauterine and in the first years of life. The second is that EDCs that alter developmental programming, *i.e.*, the "set point", predispose one to weight gain and obesity later in life[14]. Another important conclusion is that habitual causes such as diet and exercise are not the only root of obesity, as we have seen in studies of obesity. It has also been shown that genes and environment (especially in the intrauterine and subsequent postpartum years), and the interactions between them are quite important.

In his article, Heindel *et al*[14] explains the importance of the obesogen hypothesis for the treatment of obesity and states that the obesogen hypothesis has shifted attention from genetics to the environment as a major cause of obesity. The focus of discussion has shifted from mostly unsuccessful treatment to prevention, and the timing of predisposition to obesity has shifted from adulthood to the developmental age. Therefore, it was helpful for us to focus on a different age group and the protection of that age group. Furthermore, this hypothesis gives us hope that the pandemic of obesity can be prevented by arguing that obesity is a disease acquired by environmental exposure, and therefore preventable, rather than a genetic inheritance.

DIABETOGEN HYPOTHESIS

The diabetogen hypothesis is similar and parallel to the obesity hypothesis. The main reason for this hypothesis is that some EDCs, especially POPs, predispose to T2DM independently of obesity[13]. Many studies have shown that POPs and others, increases peripheral insulin resistance and alters insulin production and secretion[13,76]. The diabetogenic effect of EDCs, at least partially, explains why some people are metabolically obese despite being of normal weight[77].

CLINICAL AND MECHANISTIC EVIDENCE

Due to ethical issues, it is quite difficult to design a double-blind trial on EDCs. For this reason, the studies can be divided into these four groups: Embryological analysis of EDC exposure (mainly in rodent models), studies of the mechanism of exposure (gene expression and epigenetic changes in cell and tissue cultures), studies examining the association between EDC and diseases (most of which are epidemiological studies), and reports of occupational or acute exposure to one or more chemicals known to be EDCs.

BPA is mainly used to make epoxy resins and polycarbonate. It is by far one of the most commonly exposed EDCs because of its widespread use and, particularly, its long-term use in sectors such as toys and food packaging. As a result, epidemiological studies have concentrated on BPA and phthalates in general. Only the most up-to-date studies and studies with divergent results are included here, because the study models are generally similar and there are no obvious differences between the outcomes.

Clinical evidence for BPA as an obesogen

Various recent studies have found a correlation between BPA and obesity. BPA urine levels were strongly correlated with BMI and waist circumference in 296 women of reproductive age[78]. In the study conducted by Choi *et al*[79], it measured the prenatal BPA exposures of 59 children. They classified those remaining above the 80th percentile as high exposure and others as low exposure. The study examined 594 obesity-associated CpG sites from children's methylation profiles. As a result, high methylation in the insulin-like growth factor 2 receptor region was detected in the 2-year-old high exposure group. This study has strengthened the notion that BPA exposure affects humans through the mechanism of methylation[79].

Extensive studies published in recent years clearly reveal the relationship between BPA and obesity. A study of 888 middle-aged and elderly Chinese conducted in China found a positive association between urinary BPA concentration and central obesity[80]. A study by the Canadian Health Measures Survey found a positive correlation between urinary BPA levels and BMI-defined obesity. However, no relationship was found between waist circumference and urinary BPA using the standard cut-offs. In addition, for each natural logarithmic unit increase in urinary BPA concentration, an increase in the BMI of 0.33 kg/m² and a waist circumference of 1 cm was observed[81]. The National Health and Nutrition Examination Survey (NHANES) studies in 2003-04 and 2005-06 found a significant positive association with obesity when comparing the highest and lowest quartiles of urinary BPA[82]. This study was adjusted for traditional risk factors. Likewise, the Korean national health study used the Covariate-Adjusted Standardization (CAS) Method to prevent factors such as age, gender, education, urinary creatinine, income, alcohol, and smoking from affecting the study. After using the CAS method, a positive relationship with obesity was determined by comparing the highest and lowest quartiles of urinary BPA[83]. Wu *et al*[84] showed in their meta-analysis that there was a positive correlation between BPA exposure and obesity. According to the dose-response analysis, an increase of 1 ng/mL BPA causes an increase of 11% risk in obesity.

Clinical evidence for BPA as a diabetogen

Evidence from individual epidemiological studies is usually inconsistent in regards to the association of BPA exposure and T2DM, so it is unclear whether exposure to BPA is a risk factor for the development of T2DM. Population ethnicity, lifestyle, eating habits, use of BPA-containing products, different sample size, and differences in T2DM criteria are the factors that may account for the inconsistent findings[85]. One of the meta-analysis ($n = 41.320$) included 16 epidemiological studies (12 cross-sectional, 2 case-control, 1 prospective) that showed a positive association between BPA levels and T2DM risk with a pooled OR of 1.28 (95%CI 1.14-1.44)[86]. Another meta-analysis, including 41 cross-sectional and 8 prospective studies from ethnically diverse populations, evaluated the association of dioxin, PCB, chlorinated pesticide, BPA and phthalate with T2DM, and related metabolic features. Serum concentrations of dioxins, PCBs, and chlorinated pesticides were significantly associated with T2DM risk. Urinary concentrations of BPA and phthalates were also associated with T2DM risk with pooled RR of 1.45 (95%CI 1.13-1.87) and 1.48 (95%CI 0.98-2.25), respectively[87].

On the other hand, few studies have shown that BPA can trigger diabetes independent of obesity. Silver *et al*[88] analyzed the NHANES results and Tai *et al*[89] analyzed the CMHS results and found a positive correlation between BPA and glycated haemoglobin. Another study reversed the experimental mechanism. When the study compared urinary BPA in individuals with impaired glucose tolerance (IGT) and normal glucose tolerance (NGT), the results showed that urinary BPA was higher in individuals with IGT[90]. When a similar study was conducted with participants with T2DM and NGT, it was found that participants with T2DM had higher urinary BPA[91]. In addition, BPA has also been found to be positively associated with high blood insulin resistance[76,87], prediabetes risk[92], and T2DM[93,94].

Clinical evidence for BPA substitutes

Many countries have regulated BPA. BPA was banned from bottles in Canada in 2008, Denmark in 2009, France in 2010, and the European Union and Turkey in 2011[95-97]. In addition, Sweden and France banned the use of BPA in food products designed for children under the age of 3 in 2011 and 2013, respectively[96]. Such regulations have led to the development of substitutes such as BPS and BPF.

However, as previously mentioned, the hormonal activities of BPA substitutes (generally BPS, BPF, BPAF) were also of the same magnitude and similar effect as BPA in the *in vivo* and *in vitro* studies[46]. A NHANES analysis showed the positive association between BPS and obesity, particularly in children and adolescents[98,99]. When Duan *et al*[100] examined BPA equivalents BPAF and BPS, they reported a positive correlation with T2DM.

A group analyzed the NHANES 2003-2014 results. They state that the urinary BPA concentration has decreased over the years in a trend analysis. Bans on BPA since 2009 may have contributed to this. As a result, the researchers indicated that the positive relationship between obesity and urinary BPA diminished between 2009 and 2014[101]. Since then however, obesity has been on the rise. It is noteworthy that the oral bioavailability of EDC candidate chemicals such as BPS is higher than BPA [102] and that the half-life is longer[103].

The fundamental mechanistic principle of obesogen

EDCs can mimic hormonal actions through the nuclear hormone receptor superfamily like steroid hormone receptors, thyroid hormone receptors, retinoid X receptors (RXR), peroxisome proliferator-activated receptors (PPAR), liver X receptors, and farnesoid X receptors[104]. The nuclear hormone receptor PPAR gamma dimerize with RXR and bind to PPAR-responsive DNA regulatory elements, which leads to the controlling of fat cell differentiation. In this way, genes responsible for adipogenesis, lipid, and glucose metabolism are controlled[105]. Dysregulation of PPAR γ can cause obesity and metabolic disorders. PPAR γ can bind to BPA, perfluorinated compounds (PFCs) and phthalates leading

to stimulation of adipogenesis *in vitro* and *in vivo* by stimulating the differentiation of preadipocytes to mature adipocytes[105]. The differentiation of adipocytes is a complex process. The expression of binding proteins CCAAT/enhancer beta (C/EBP β) and C/EBP δ induces adipogenesis firstly. At the second stage, the activity of those proteins leads to the activation of PPAR γ and C/EBP α [106]. There are different models of cell lines which are embryonic 3T3-L1 and 3T3-F442A cell lines that can be stimulated to differentiate into adipocytes under chemical exposure[28].

White adipose tissue (WAT) is the main adipose tissue for the fat storage. But specific adipose tissue like brown adipose tissue (BAT) and beige fat are also present. Those have thermogenic features primarily mediated by the expression of uncoupling protein 1 (UCP1). BAT is activated at birth for thermogenesis, but with increasing age, this activity of BAT decreases. Beige fat differentiates from white adipocytes postnatally in response to cold temperatures, thyroid hormone, adipokines, immune cells, and cytokines. Those two thermogenic adipose tissues have dense mitochondria and UCP1 leading to increased basal metabolic rate, and metabolizing excess fat as anti-obesity features. The loss of BAT called as whitening, and decreases in the beiging of white adipose tissue, are associated with aging, obesity, and metabolic diseases[107]. Transcriptional regulation of peroxisome proliferator-activated receptor- γ coactivator-1 α (PGC1 α), and UCP1 is performed by thyroid receptors and PPARs. EDCs interfere with thyroid or PPAR signalling, so in that way, EDCs can cause dysfunction in brown and beige fat depots (Figure 2). Female offspring from dams exposed to BPA had an increment in weight of the interscapular BAT depot and the expression of UCP1[108]. However, male offspring demonstrated reduced brown adipogenesis and BAT activity. An agonistic effect of BPA on the estrogen receptor, which is necessary for mitochondrial biogenesis and thermogenesis in BAT, can explain the sexual dimorphism observed with BPA[109].

The other potential explanation of BPA effect on WAT and BAT is the distribution of macrophage subtypes. When M1 macrophages are activated, WAT inflammation occurs through secretion of proinflammatory cytokines including interleukin-1 β (IL-1 β), IL-6, and tumor necrosis factor- α (TNF- α). M2 macrophages secrete anti-inflammatory cytokines such as IL-4 and IL-10[110]. M1 macrophage infiltration accompanies whitening of brown fat, suggestive of BAT dysfunction (Figure 2). Some phytochemicals and phthalates also can promote M2 macrophage polarization and beiging in WAT[111, 112].

BPA prevents the release of adiponectin while it increases pro-inflammatory cytokines by acting on adipocytes and macrophages. BPA also regulates some genes like fatty acid binding protein 4 (FABP4) and a cluster of differentiation 36 (CD36). FABP4 binds to lipid A resulting in accumulation of fatty acids. Up-regulation of FABP4 in adipose tissue prevents fatty acid β oxidation. Increased fatty acid levels go to the ectopic organs such as the liver resulting in lipotoxicity[113]. Besides a lipid accumulation effect of BPA leading to obesity, two other mechanisms to explain obesity due to BPA exposure is defined (Figure 3). BPA can result in an interruption of the neuroendocrine system in the central nervous system. Exposure to BPA can stimulate the release of Agouti related peptide (AgRP) and neuropeptide Y (NPY) and can decrease the level of proopiomelanocortin (POMC). AgRP and NPY are the orexigenic hormones inducing appetite. BPA also can have an effect on gut bacterial dysbiosis. BPA reduces gut small chain fatty acid (SCFA) and increases systemic lipopolysaccharide levels resulting in chronic low-grade inflammation and altered lipid homeostasis[113] (Figure 3).

The potential mechanism of diabetogen

The studies provide a strong support for an association between BPA, β cell function and insulin resistance[85]. In rat insulinoma cell lines, BPA decreases cell viability, disrupts glucose stimulated insulin secretion (GSIS), and induces apoptosis in a dose-dependent manner. BPA causes an increased expression of pro-apoptotic Bax protein and a reduced expression of anti-apoptotic Bcl-2[114]. It was shown that β cell damage due to BPA can be through the interaction of BPA with human islet amyloid polypeptide (hIAPP) leading to islet amyloid aggregate formation[115].

Alonso-Magdalena *et al*[116] demonstrated that acute exposure to BPA induces a rapid decrease in the glycemia within 30 min of the first injection by increasing in plasma insulin. Sustained exposure to BPA resulted in higher β -cell insulin levels due to estrogen receptor stimulation. Both the estrogen and the BPA treated mice showed 1.7- and 1.53-fold higher circulating insulin levels, respectively with normal blood glucose levels mimicking insulin resistance features. BPA has a non-monotonic dose-response effect, which means the most effective dose may not necessarily be the highest one. There is an inverted U-shaped relationship between increasing BPA doses and GSIS. While a dose of 0.1 μ g/L BPA causes an increase in GSIS, doses of 25 and 250 μ g/L BPA cause a decrease in GSIS[117,118].

The effect of EDCs as obesogens and diabetogens causing obesity and T2DM is summarized in Figure 4.

CONCLUSION

Humans are exposed to a variety of EDCs with obesogenic and diabetogenic effects. Those chemicals change the hormonal balance with different mechanisms of action. The exposure to obesogens can

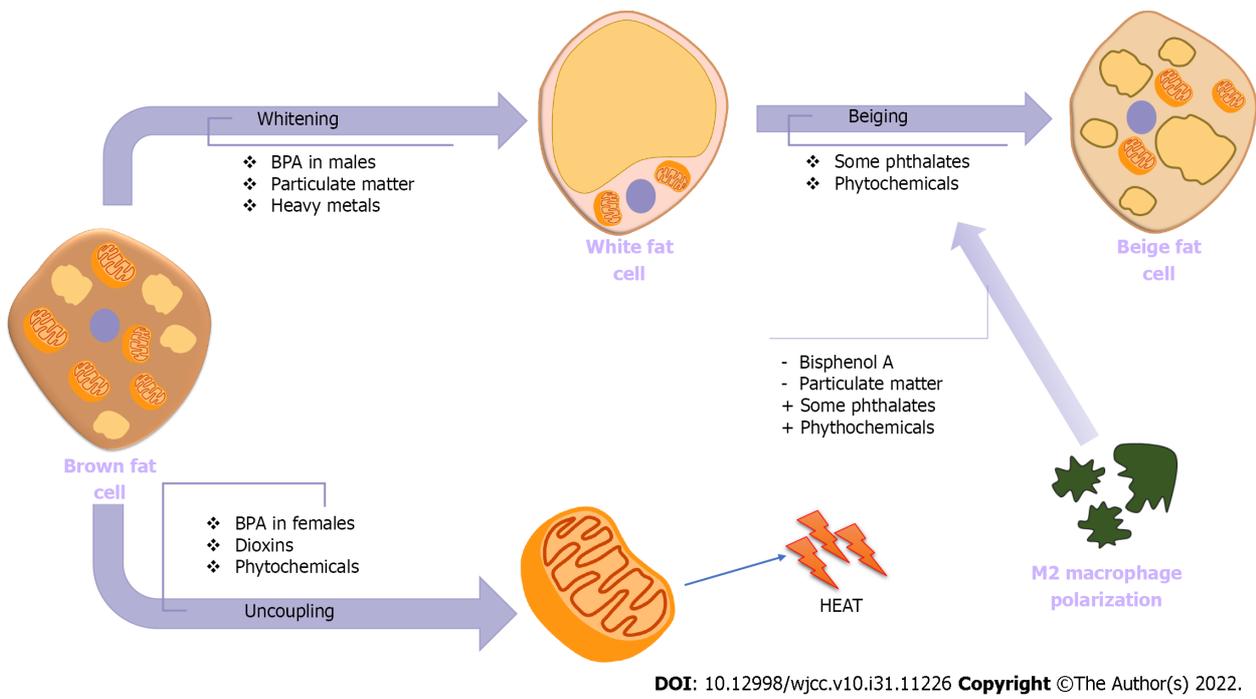


Figure 2 Potential effects of endocrine-disrupting chemicals on brown and beige adipogenesis. BPA: Bisphenol A.

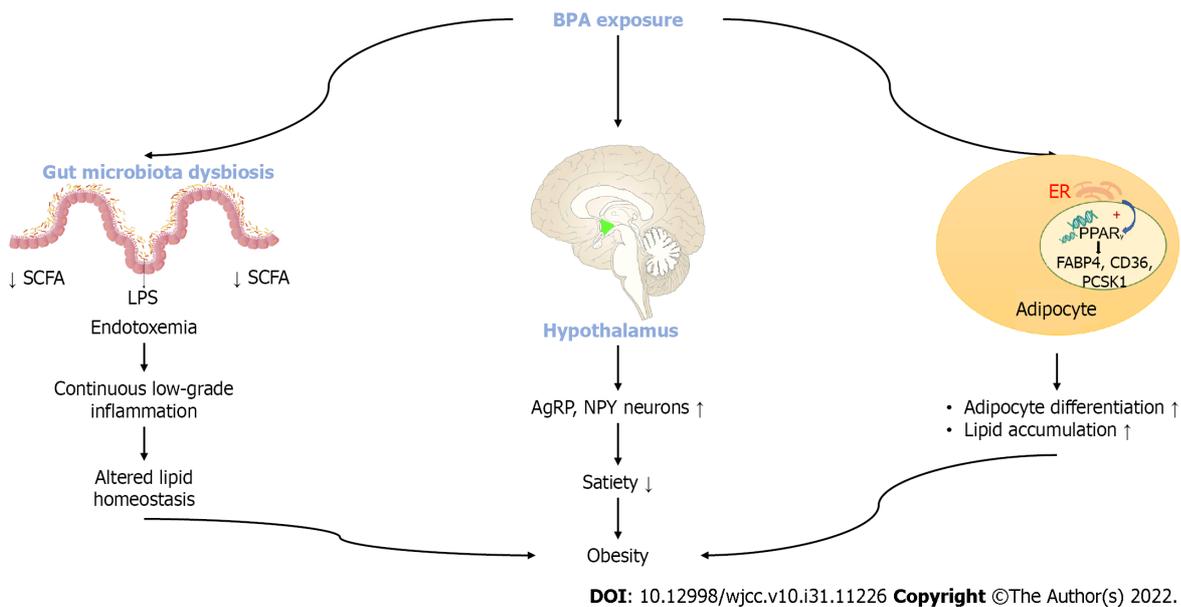
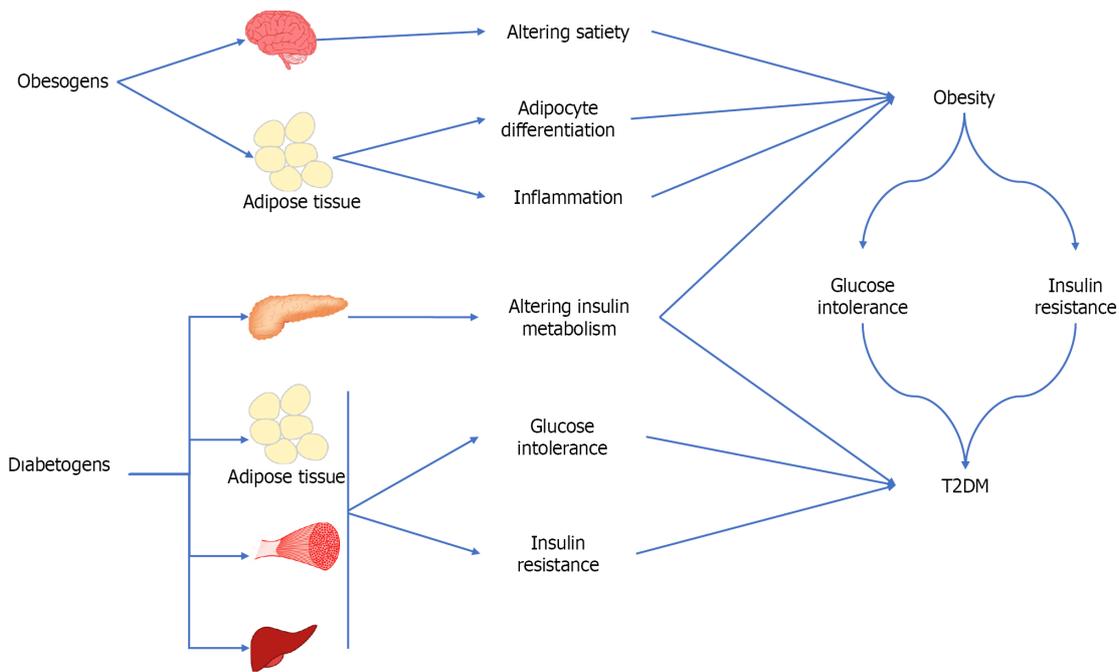


Figure 3 Changes in the hypothalamus, adipocyte and gut microbiota caused by bisphenol A exposure in favor of obesity. BPA: Bisphenol A; LPS: Lipopolysaccharide; SCFA: Small chain fatty acid; NPY: Neuropeptide Y; AgRP: Agouti related peptide; PPAR: peroxisome proliferator-activated receptors; FABP4: Fatty acid binding protein 4; CD36: Cluster of differentiation 36.

happen during the different stages of life. In this context, perinatal exposure can be important as far as the permanent and transgenerational effects are concerned. EDCs promote adipogenesis leading to fat accumulation, which causes alteration in lipid metabolism and satiety as obesogens. EDCs have shown the potential to induce adipose tissue dysfunction not only in white adipocytes but in brown and beige fat as well. Besides an obesogenic effect, EDCs can cause T2DM through alteration in β cell function and morphology, and insulin resistance. The studies related to EDCs and obesity, and T2DM are not enough methodologically to show causality. In this respect, randomized clinical trials are needed to investigate the association between obesogen, diabetogen, and the related metabolic clinical picture. Future studies will be important to take political action and to increase the awareness of the population about the exposure to obesogen and diabetogen EDCs.



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Figure 4 Summary of the effects of obesogen and diabetogen on tissues and the relationship of these effects with obesity and diabetes. T2DM: Type 2 diabetes mellitus.

FOOTNOTES

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