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Teratogenic mechanisms of medical drugs

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BACKGROUND: Although prescription drug use is common during pregnancy, the human teratogenic risks are undetermined for more than 90% of drug treatments approved in the USA during the past decades. A particular birth defect may have its origins through multiple mechanisms and possible exposures, including medications. A specific pathogenic process may result in different outcomes depending upon factors such as embryonic age at which a drug is administered, duration and dose of exposure and genetic susceptibility. This review focuses on the teratogenic mechanisms associated with a number of medications.

METHODS: We used three methods to identify the teratogenic mechanisms of medications: the MEDLINE and EMBASE databases, two recent books on teratogenic agents and a list of drugs classified as U.S. Food and Drug Administration class D or X. Mechanisms were included only if they are associated with major structural birth defects and medications that are used relatively frequently by women of reproductive age.

RESULTS: We identified six teratogenic mechanisms associated with medication use: folate antagonism, neural crest cell disruption, endocrine disruption, oxidative stress, vascular disruption and specific receptor- or enzyme-mediated teratogenesis. Many medications classified as class X are associated with at least one of these mechanisms.

CONCLUSIONS: Identifying teratogenic mechanisms may not only be relevant for etiologic and post-marketing research, but may also have implications for drug development and prescribing behavior for women of reproductive age, especially since combinations of seemingly unrelated prescription and over the counter medications may utilize similar teratogenic mechanisms with a resultant increased risk of birth defects.

Key words: congenital abnormalities / pharmaceutical agents / pregnancy / teratology

Introduction

Since approximately half of the pregnancies in the USA are unintended (Finer and Henshaw, 2006), many women expose their unborn children to drugs before they know they are pregnant. Furthermore, prescription drug use is common during pregnancy in many other countries as well, with prevalence estimates ranging from 44 to 79% in several European countries (Olesen *et al.*, 1999; Bakker *et al.*, 2006; Engeland *et al.*, 2008). Because pregnant women were often excluded from clinical trials and data from animal studies are not always predictive for a teratogenic effect in humans, drug use by pregnant women can be considered experimental in most instances. Nevertheless, the use of medication is sometimes inevitable in the treatment of women of reproductive age and during pregnancy. Although it has clearly been shown that some drugs, e.g. thalidomide and isotretinoin, can produce birth defects, the teratogenic risks in human pregnancy are undetermined for more than 90% of drug treatments approved in the USA in the last decades [Lo and Friedman, 2002; Physicians' Desk Reference, 2009 or the website of the Teratogen Information System (TERIS) for more details]. Birth defects are the leading cause of infant mortality and the etiologic pathways are largely unknown for many defects. A particular birth defect may be caused by many different factors (e.g. genetics, environmental agents, medications, physical conditions) as well as by different mechanisms, whereas a specific pathogenic process may result in different outcomes for chemical or drug exposures depending upon such factors as embryonic age, duration and dose of exposure and genetic susceptibility (Pollard, 2007; Schaefer *et al.*, 2007). In addition, maternal determinants, including drug administration, distribution, metabolism, and excretion, may also play an important role. Although the mechanisms by which drugs may cause birth defects are still not completely understood, we will present an overview of the most important teratogenic mechanisms known today. Identifying these mechanisms may be relevant for drug development, (post-marketing) research and prescribing of medications to women in their reproductive years.

Methods

We used three methods to identify the most important teratogenic mechanisms associated with medical drug use. First, in January 2009, the MEDLINE and EMBASE bibliographic databases were used as search engines employing a combination of keywords, including 'birth defects', 'congenital abnormalities', 'mechanism', 'teratogenesis', 'abnormalities, drug-induced', 'pregnancy' and 'pharmaceutical preparation'. Only articles that were published in the English language were included. Secondly, two recent books on teratogenic agents by Shepard and Lemire (2007) and Schaefer *et al.* (2007) were hand-searched for additional mechanisms. Finally, all medications classified by the U.S. Food and Drug Administration (FDA) as class D ('the potential benefits from the use of the drug in pregnant women may be acceptable despite its potential risks') or class X ('contraindicated in women who are or may become pregnant') (U.S. Food and Drug Administration, 2003; Schwarz *et al.*, 2007) were screened. Only mechanisms producing major structural birth defects associated with medications that are relatively frequently used by women of reproductive age (defined as an annual prescription rate of $>0.5\%$, if known) were included in this review. These mechanisms are folate antagonism, neural crest cell disruption, endocrine disruption, oxidative stress, vascular disruption and specific receptor- or enzyme-mediated teratogenesis. It should be noted that, so far, some of these mechanisms are principally understood from animal models; however, these mechanisms may produce birth defects in humans as well. In addition, some drugs may be involved in multiple mechanisms for producing birth defects.

Folate Antagonism

Folate, the generic term for a water-soluble B vitamin, occurs in high concentrations in certain natural foods (fruits, leafy green vegetables, beans and liver) as polyglutamate. The synthetic form, folic acid (a monoglutamic acid), is used in food fortification and vitamin preparations. Folic acid has a higher bioavailability than food folate (Brouwer *et al.*, 1999). Folate is converted through two reduction reactions by dihydrofolate reductase (DHFR) to the naturally bioactive form tetrahydrofolate (THF), which is converted into 5-methyltetrahydrofolate (5-MTHF) monoglutamate. 5-MTHF is the main form of folate in the blood circulation and is transported into cells by three routes: by membrane-associated receptors, by a carrier-mediated system, the reduced folate carrier, and by passive diffusion (Antony, 1992; van der Put *et al.*, 2001). Inside the cell, it acts as an essential co-enzyme in many biochemical reactions by being an acceptor or donor of one-carbon units in, for example, purine and pyrimidine synthesis and DNA methylation reactions (Fig. 1). Since rapidly proliferating tissues require DNA synthesis the most, it is obvious that folate-dependent reactions are essential for fetal growth and development and that folate requirements increase during pregnancy. In addition, DNA methylation is known to be involved in the epigenetic control of gene expression during development.

Several drugs disturb the folate metabolism and may have a teratogenic effect through inhibition of the folate methylation cycle (Table I). Two general groups of drugs act as folate antagonists. The first group consists of competitive inhibitors of DHFR and includes methotrexate, sulfasalazine, triamterene and trimethoprim, which block the conversion of folate to THF by binding irreversibly to the enzyme (Lambie and Johnson, 1985). They are used in the treatment of a variety of diseases, such as inflammatory bowel disease, rheumatoid arthritis, hypertension and urinary tract infections. The second group of drugs may antagonize other enzymes in the folate metabolism, impair folate absorption or increase folate degradation. This group primarily consists of anti-epileptic drugs, including valproic acid, carbamazepine and phenytoin. The teratogenicity of folate antagonists in humans was first suggested by reports of women who were given aminopterin in the first trimester of pregnancy to induce abortion (Thiersch, 1952). Some anti-epileptic drugs, e.g. carbamazepine and valproic acid, are generally known to increase the risk of folate-sensitive birth defects, such as neural tube defects, orofacial clefts and limb defects. So far, only three studies have been conducted to determine the effect of folate antagonists as a group on the occurrence of birth defects in humans, but the results are inconsistent, particularly for DHFR inhibitors (Hernández-Díaz *et al.*, 2000, 2001; Meijer *et al.*, 2005). In addition, polymorphisms in genes associated with the folate metabolism, including methylenetetrahydrofolate reductase (MTHFR; Botto and Yang, 2000; van Rooij *et al.*, 2003), methionine synthase reductase (MTRR; van der Linden *et al.*,

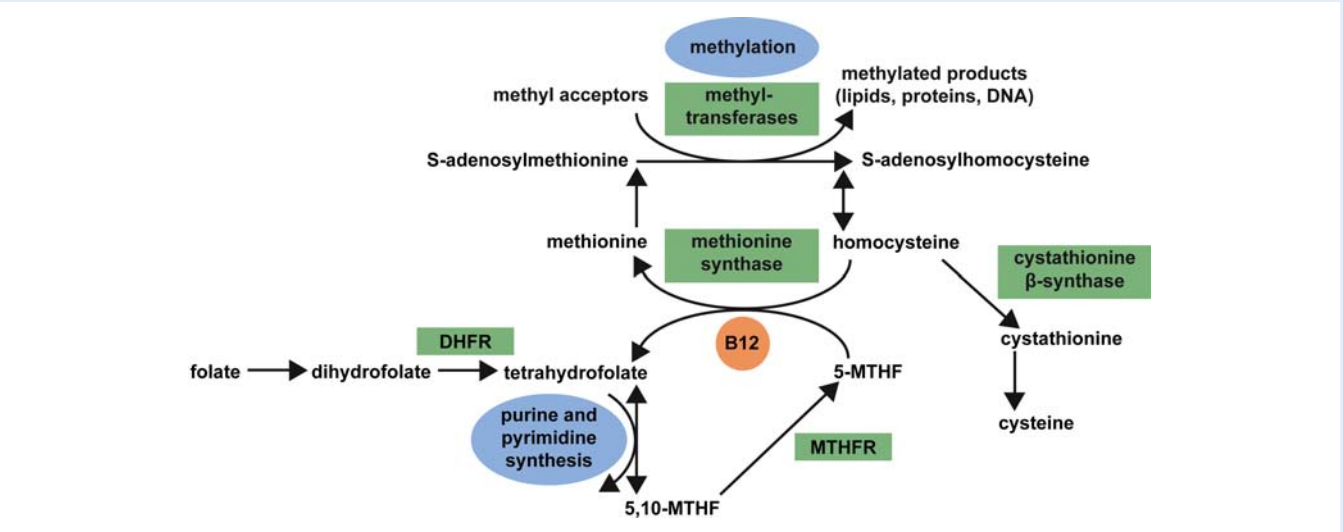

Figure 1 Folate–homocysteine–methionine metabolism. B12, vitamin B_{12}; DHFR, dihydrofolate reductase; MTHF, methyltetrahydrofolate; MTHFR, methyltetrahydrofolate reductase.

Table 1 Medical drugs associated with folate antagonism

Medication	Main indication	Interference with folate metabolism
Carbamazepine	Epilepsy, bipolar disorder	Impairment folate absorption
Cholestyramine	Hypercholesterolemia	Impairment folate and vitamin B_{12} absorption
Cyclosporine	Transplants, psoriasis, atopic dermatitis	Possible interference folate dependent remethylation
Lamotrigine	Epilepsy, bipolar disorder	Inhibition DHFR
Metformin	Diabetes	Interference vitamin B_{12}
Methotrexate	Cancer, some auto-immune diseases (rheumatoid arthritis, psoriasis)	Inhibition DHFR
Nicotinic acid	Hypercholesterolemia	Decrease acitivity CBS
Phenobarbital	Epilepsy	Impairment folate absorption
Phenytoin	Epilepsy	Impairment folate absorption, decrease activity methionine synthase, possible decrease activity MTHFR
Primidone	Epilepsy	Impairment folate absorption
Pyrimethamine	Malaria	Inhibition DHFR
Sulfasalazine	Inflammatory bowel disease, rheumatoid arthritis	Inhibition DHFR
Triamterene	Hypertension, edema	Inhibition DHFR
Trimethoprim	Urinary tract infection	Inhibition DHFR
Valproic acid	Epilepsy, migraine headache	Antimetabolite of folate

CBS, cystathione β-synthase; DHFR, dihydrofolate reductase; MTHFR, methyltetrahydrofolate reductase.

2006) and methylenetetrahydrofolate dehydrogenase (MTHDF1; Parle-McDermott *et al*., 2006), may lead to differences in the susceptibility of individuals to folate antagonists.

Experimental studies in a number of animal species demonstrated that folate deficiency causes intrauterine death, growth retardation and various congenital malformations (Jordan *et al*., 1977; Li *et al*., 2005). The fact that folic acid supplementation in the periconceptional period decreases the risk of neural tube defects in humans (Lumley *et al*., 2001) strongly suggests a causative role of folate deficiency in the etiology of these defects. Recently, low blood folate status has been associated with an increased risk of neural tube defects (Candito *et al*., 2008; Zhang *et al*., 2008). Besides folate deficiency, a low maternal vitamin B_{12} (cyanocobalamin) status has also been shown to be an independent risk factor for neural tube defects (Ray *et al*., 2007; Molloy *et al*., 2009). Vitamin B_{12} is cofactor to methionine synthase, which converts homocysteine into methionine. Therefore, a shortage of vitamin B_{12} also leads to a distorted folate metabolism.

The exact mechanism by which disturbances of the folate metabolism increase the risk of neural tube defects is unclear. Women

who carry a fetus with a neural tube defect have significantly higher levels of homocysteine in plasma and amniotic fluid than control subjects (Mills *et al*., 1995; Steegers-Theunissen *et al*., 1995), which may be caused by folate deficiency. Several hypotheses have been proposed to explain how increased levels of homocysteine, or the accompanying decreased methionine levels, could cause neural tube defects. First, homocysteine itself may be teratogenic during the neurulation process, causing dysmorphogenesis of the neural tube, heart and ventral wall in chick embryos (Rosenquist *et al*., 1996). In rat and mouse embryos, however, increased homocysteine levels did not cause neural tube defects (van Aerts *et al*., 1993; Bennett *et al*., 2006). Therefore, it seems that elevated plasma homocysteine levels itself may not cause neural tube defects, but are a biomarker of disturbances in the methylation cycle which may result in neural tube defects. More likely, intracellular accumulation of homocysteine leads to increased levels of *S*-adenosylhomocysteine, which is a competitive inhibitor of many methyltransferases, through which gene expression, protein function and the lipid and neurotransmitter metabolisms might be dysregulated (van der Put *et al*., 2001; Blom *et al*., 2006). Furthermore, the decreased remethylation of homocysteine to methionine leads to decreased levels of *S*-adenosylmethionine, which is the most important methyl-group donor in the methylation cycle. As a result, neurulation could be disturbed by inadequate gene and amino acid methylation (van der Put *et al*., 2001). Methylation steps also play an important role in the metabolism of lipids and neurotransmitters and in detoxification of exogenous substances. This stresses the crucial role of the folate metabolism for normal cellular function, especially during cell division and differentiation. This hypothesis is supported by previous studies showing that methionine is required for normal neural tube closure in rat embryos (Coelho and Klein, 1990; Vanaerts *et al*., 1994). Disturbances in folate metabolism are also thought to play a role in the etiology of orofacial clefts (Werler *et al*., 1999; van Rooij *et al*., 2004; Wilcox *et al*., 2007), heart anomalies (Czeizel, 1993; Shaw *et al*., 1995), limb reduction defects (Czeizel, 1993; Shaw *et al*., 1995; Werler *et al*., 1999), anal atresia (Myers *et al*., 2001) and urinary tract anomalies (Czeizel, 1993; Werler *et al*., 1999) since folic acid supplementation, alone or in multivitamins, seems to have a protective effect on the occurrence of these birth defects, although the evidence is not as strong and consistent as for neural tube defects. Therefore, it seems likely that medications that act as folate antagonists may cause various birth defects through similar mechanisms.

Neural Crest Cell Disruption

The neural crest is an important, pluripotent cell population that originates in the neural folds. The neural crest cells can be divided into two major populations: the cranial and truncal neural crest. During neurulation, the neural crest cells detach from the neural folds and migrate into the embryo to give rise to numerous structures. In the craniofacial region, various cell types and structures, including intramembranous bone, cartilage, nerves and muscles, are derived from the cranial neural crest. The truncal neural crest produces important components of the peripheral nervous system (Larsen, 2001). The cardiac neural crest is a subpopulation of the cranial neural crest, which migrate into the cardiac outflow tract to mediate septation and into other derivatives of the pharyngeal arches, such as the thymus and the thyroid and parathyroid glands (Kirby and Waldo, 1990). Therefore, neural crest-related cardiovascular malformations include aortic arch anomalies and conotruncal defects (Nishibatake *et al*., 1987). Membranous ventricular septal defects are also neural crest-related, since the membranous part of the interventricular septum originates from the cardiac neural crest, whereas the muscular part originates from the mesenchyme (Waldo *et al*., 1998). Non-cardiovascular defects that have been proposed to be neural-crest related are craniofacial malformations (Chai and Maxson, 2006), esophageal atresia (Otten *et al*., 2000; Morini *et al*., 2001) and abnormalities of the pharyngeal glands (Bockman and Kirby, 1984).

Proper induction, migration, proliferation and differentiation of neural crest cells are tightly regulated. A variety of molecular signals and receptors are implicated in neural crest cell development. Fibroblast growth factors may be involved in the induction of neural crest cells (LaBonne and Bronner-Fraser, 1998). Integrins, a family of cell surface receptors, play a role in the interaction of neural crest cells with the extracellular matrix (Strachan and Condic, 2008), whereas interactions between neural crest cells are mediated by cadherins (Nakagawa and Takeichi, 1998). It has been suggested that Pax3 is necessary for the fine tuning of the migration process of cardiac neural crest cells (Epstein *et al*., 2000). Endothelins and their receptors may be required for the migration, differentiation and proliferation of neural crest cells (Clouthier *et al*., 1998; Yanagisawa *et al*., 1998). Therefore, drugs that interfere with these molecular pathways, such as bosentan (Clozel *et al*., 1994), which is indicated for the treatment of pulmonary hypertension and to reduce new digital ulcers associated with systemic sclerosis, may induce neural crest-related malformations. In addition, *in vivo* and *in vitro* experiments suggested that altering levels of folate and/or homocysteine cause abnormalities of cardiac neural crest cell migration, differentiation and cell cycle progression (Stoller and Epstein, 2005), thereby connecting this teratogenic mechanism with folate antagonism. However, one of the most important signaling molecules in neural crest cell development is retinoic acid, the biologically active form of vitamin A. Excesses (Lammer *et al*., 1985), as well as shortages (Wilson *et al*., 1953), of retinoic acid seem to cause neural crest-related malformations, indicating that proper retinoid homeostasis is necessary for normal development. Embryonic retinoic acid synthesis and degradation are performed by retinal dehydrogenases and CYP26, respectively (Fujii *et al*., 1997; Duester, 2000). In addition to retinoids used in the treatment of dermatologic conditions, such as tretinoin, isotretinoin and etretinate, other drugs that inhibit these enzymes may also be involved in disturbances of retinoid homeostasis. It has been suggested that retinoid teratogenicity is mediated by the retinoic acid receptors (RARs) and retinoid X receptors (RXRs; Elmazar *et al*., 1997). These nuclear ligand-inducible receptors are transcription factors themselves and affect other downstream genes that are important in development (Morriss-Kay, 1993). This hypothesis is strengthened by the fact that mice lacking RARs and RXRs show developmental defects similar to those caused by vitamin A deficiency, including neural crest-related malformations (Kastner *et al*., 1994; Lohnes *et al*., 1994). Alternatively, increased *Hox* gene expression may underlie the detrimental effects of excess retinoic acid on the development of structures derived from the neural crest (Krumlauf, 1994; Waxman and Yelon, 2009).

Endocrine Disruption: Sex Hormones

Since the 1940s, a number of drugs have been developed to mimic or inhibit the actions of hormones, including diethylstilbestrol (DES), oral contraceptives and hormones used in fertility treatment. These medications and other endocrine disrupting chemicals (EDCs), such as bisphenol A and phthalates, may interfere with the physiologic functions of endogenous hormones by affecting their release, binding or metabolism. Their actions may not only depend upon their affinity or specificity for the estrogen and/or androgen receptors, but also upon their ability to activate or inhibit receptor-mediated actions, which are dependent upon the absorption, distribution, metabolism and excretion (ADME) of these molecules as well. The actions of EDCs *in utero* have been of concern because of their possible impact on the developing reproductive systems, especially since treatment of pregnant women with the synthetic estrogen DES led to an increased risk of vaginal adenocarcinoma in their daughters (Herbst *et al*., 1971). Since human effects were identified first, animal studies have been conducted to confirm these clinical observations and to investigate the differences between synthetic and natural estrogen actions on the embryo or fetus (McLachlan, 1981; Henry *et al*., 1984). It is well known that human sex hormone-binding globulin has a substantially higher affinity for estradiol than for DES or other synthetic hormones (Hodgert Jury *et al*., 2000), which suggests that DES may be more readily available to cross the placenta. DES is also metabolized to reactive intermediates which covalently bind (Metzler, 1981; Miller *et al*., 1982), whereas estradiol is not metabolized to similar reactive intermediates (Klopper, 1980; Slikker *et al*., 1982). In addition, α-fetoprotein binds estradiol but not DES (Sheehan and Young, 1979). So besides the capability of the placenta to reduce the transfer of estradiol, plasma binding and metabolism of this endogenous hormone to less active estrogens may be important defense mechanisms for the fetus to reduce the actions of estradiol, which are apparently not available for the synthetic estrogen DES.

Besides an increase in the risk of vaginal adenocarcinoma in daughters, prenatal exposure to DES has also been associated with an increase in reproductive disorders in sons (Giusti *et al*., 1995) and grandsons (Klip *et al*., 2002; Brouwers *et al*., 2006). In male animals, prenatal exposure to EDCs with estrogenic or anti-androgenic properties have been shown to cause hypospadias and cryptorchidism (McMahon *et al*., 1995; Kim *et al*., 2004; Christiansen *et al*., 2008). In addition to drugs that influence endocrine homeostasis as their primary mechanism of action, coatings for oral medications, such as mesalamine and omeprazole, may be a source of EDC exposure (Hernández-Díaz *et al*., 2009). These enteric coatings contain phthalates, which may affect human male reproductive development due to their anti-androgenic properties (Swan *et al*., 2005). Additionally, other preparations may contain phthalates as plasticizers (Hauser *et al*., 2004), but it should be noted that phthalates do not bio-accumulate and are excreted rapidly in contrast to some other EDCs. The susceptibility to EDCs may also vary greatly between individuals due to genetic factors (Giwercman *et al*., 2007). Therefore, it is questionable whether the levels of phthalates in medications in particular are high enough to produce male reproductive tract anomalies in humans. In epidemiologic studies, omeprazole and mesalamine have not been associated with an increased risk of major birth defects (Diav-Citrin *et al*., 1998; Gill *et al*., 2009).

Male development is more susceptible to endocrine disruption than female development because of its hormone dependence (Sharpe, 2006). However, since synthetic hormones and EDCs may affect endocrine homeostasis in multiple ways, the underlying teratogenic mechanisms are often difficult to unravel. Because of considerable species differences and markedly different estrogen levels in normal human pregnancy compared with normal rodent pregnancy, it is debatable whether certain mechanisms also apply to humans. Male sexual differentiation generally depends on a balanced androgen/estrogen ratio. In mice, estrogens impair fetal Leydig cell development, and, as a consequence, testosterone production is decreased (Delbès *et al*., 2005). Phthalates that induce male reproductive disorders in rats mainly do so through inhibition of steroidogenesis by the fetal testis (Parks *et al*., 2000; Mylchreest *et al*., 2002), but this does not occur *in vitro* with human fetal Leydig cells (Lambrot *et al*., 2009). Testosterone secretion is responsible for most of the masculinization process, including the development of the male reproductive tract and external genitalia. Therefore, compromised testosterone production may result in hypospadias. In addition, estrogen exposure also suppresses the production of insulin-like factor 3 by fetal Leydig cells (Emmen *et al*., 2000). This peptide regulates the growth of the gubernaculum (Adham and Agoulnik, 2004), which is responsible for testicular descent (Hutson *et al*., 1997). In humans, a deficiency in androgen production or action seems far more important than estrogen exposure in the etiology of cryptorchidism, since the inhibitory effects of estrogens on testicular steroidogenesis and testicular descent are only mediated through estrogen receptor α in mice (Cederroth *et al*., 2007), which is not present in the human fetal testes (Gaskell *et al*., 2003). However, this receptor is expressed and functional in human fetal penile tissue (Crescioli *et al*., 2003), so a role of estrogen exposure in the induction of hypospadias cannot be excluded. Epidemiologic studies could not confirm this, since prenatal estrogen exposure, including pharmaceutical estrogens, does not seem to be related to hypospadias and cryptorchidism (Storgaard *et al*., 2006; Martin *et al*., 2008).

Alternative mechanisms by which EDCs could cause male reproductive disorders have also been suggested. These mechanisms include disruption of the androgen signaling pathway (e.g. suppression of androgen receptor expression), resistance to anti-Müllerian hormone (AMH) and inhibition of enzymes involved in the inactivation of sex steroids. However, involvement of these mechanisms in endocrine disruption seems unlikely for various reasons. Although it has been shown that fetal exposure to chemicals that alter the androgen signaling pathway can induce hypospadias and cryptorchidism in rats (Rider *et al*., 2008), the dose needed to induce these effects is very high, which makes this mode for EDC-induced teratogenesis doubtful. AMH is primarily responsible for the regression of the Müllerian tract in male embryos (Josso *et al*., 2001) and may play a role in testicular descent (Hutson *et al*., 1997). So far, however, no compounds have been identified that affect the production or action of AMH (Sharpe, 2006). The same argument can be applied to the inhibition of estrogen sulfotransferases (and probably other enzymes involved in sex steroid metabolism), which increases cellular estradiol bioavailability. Metabolites of various polycyclic aromatic hydrocarbons inhibit

this enzyme (Kester *et al.*, 2000), but pharmacological compounds with a similar mechanism of action have not been identified yet.

Oxidative Stress

In vivo, several drugs, known as redox cycling agents and used in the treatment of, among others, epilepsy, cardiac arrhythmias and cancer, undergo single electron reduction reactions yielding radical species (Kappus, 1986). In redox cycling reactions which involve oxygen reactive oxygen species (ROS), such as hydrogen oxide, alkyl peroxides and various radicals (e.g. hydroxyl and superoxide), are generated (Kovacic and Somanathan, 2006). The creation of ROS is induced by internal and external agents, such as phagocytes, enzymes like cytochrome P450 mono-oxygenases (CYP), irradiation and exogenous chemicals. In much the same manner, the generation of ROS can be decreased or reversed by various enzymes, e.g. superoxide dismutase, catalase and glutathione reductase, and by antioxidants (Kovacic and Jacintho, 2001). Endogenous ROS serve as a second messenger in signal transduction (Hansen, 2006) and are thought to be important in ion transport, immunological host defense, transcription and apoptosis of unwanted cells (Lander, 1997; Dennery, 2007). However, ROS can also be harmful by binding covalently or irreversibly to cellular macromolecules. Oxidative stress, an imbalance between ROS generation and antioxidant defense mechanisms of a cell or tissue, causes irreversible oxidation of DNA, proteins and lipids, leading to inactivation of many enzymes and cell death (Fig. 2). In addition to damaging cellular macromolecules, oxidative stress may affect gene expression by interfering with the activity of redox-sensitive transcription factors and signal transduction by oxidizing thiols (Sahambi and Hales, 2006). During the prenatal period, this may result in birth defects and growth retardation, and in severe cases in *in-utero* death (Trocino *et al.*, 1995; Wells *et al.*, 1997; Hansen, 2006).

The developing embryo is especially susceptible to high levels of ROS because of its weak antioxidant defense, in particular in the early stages of organogenesis (Zaken *et al.*, 2000), although placental enzymes play a role in protecting the fetus against oxidative stress (Foster *et al.*, 2008). Oxidative stress is postulated to be involved in the pathogenesis of a wide spectrum of birth defects, including skeletal malformations (Sahambi and Hales, 2006; Yan and Hales, 2006), limb defects (Wellfelt *et al.*, 1999; Fantel and Person, 2002), neural tube defects (Ishibashi *et al.*, 1997; Ryu *et al.*, 2007), cleft lip/palate (Wellfelt *et al.*, 1999; Winn and Wells, 1999) and cardiovascular defects (Wellfelt *et al.*, 1999). Several drugs are known to induce oxidative stress, which is suspected to be their main teratogenic mechanism. Among these drugs are thalidomide (Hansen and Harris, 2004), phenytoin (Liu and Wells, 1994; Winn and Wells, 1999), valproic acid (Defoort *et al.*, 2006), class III antiarrhythmic drugs (Wellfelt *et al.*, 1999; Danielsson *et al.*, 2003), iron supplements (Scholl, 2005) and various chemotherapeutic drugs (Kovacic and Jacintho, 2001).

However, it is important to notice that ROS are intermediary compounds with unpaired electrons and, as a consequence, have a very short lifetime ranging from nanoseconds to milliseconds. Therefore, ROS are generally too unstable to be transferred from the mother to the developing embryo or fetus. Whenever ROS are increased in embryos, it is the result of embryonic metabolic changes rather than exposure to ROS of maternal origin (Ornoy, 2007). Increases in embryonic ROS may be caused by increased enzymatic bioactivation of proteratogens, including bioactivation of the aforementioned drugs. However, most isoforms of the CYP family, which catalyze the bioactivation of many compounds after birth, are expressed at relatively low levels during the embryonic period. Only some isoforms are expressed at levels that could be significant in teratogenesis (Juchau *et al.*, 1992; Wells and Winn, 1996). In contrast, the prostaglandin H synthases (PHSs) have a relatively high expression during the embryonic and fetal period compared with expression after birth (Winn and Wells, 1997; Parman and Wells, 2002). The peroxidase component of this enzyme can bioactivate exogenous substances, including phenytoin and related teratogens (Parman *et al.*, 1998), to toxic reactive intermediates that initiate ROS formation (Eling *et al.*, 1990). There is evidence that lipoxygenases (LPOs), which oxidize proteratogens yielding free radical intermediates, are substantially expressed in embryonic tissues as well (Yu and Wells, 1995). As a result, it is assumed that

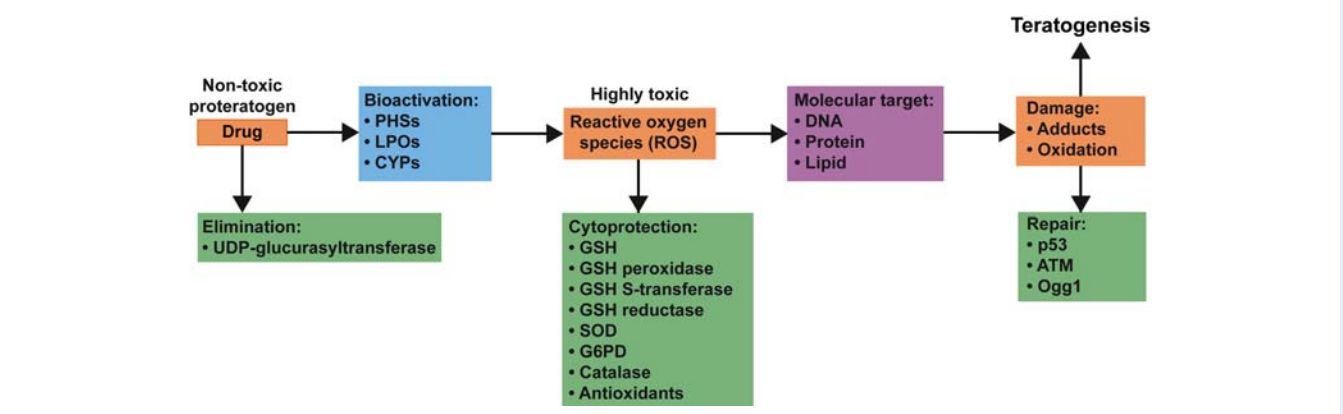

Figure 2 Molecular and biochemical determinants of oxidative stress teratogenesis. ATM, ataxia telangiectasia mutated; CYP, cytochrome P450; G6PD, glucose-6-phosphate dehydrogenase; GSH, glutathione; LPO, lipoxygenase; Ogg1, oxoguanine glycosylase 1; PHS, prostaglandin H synthase; SOD, superoxide dismutase; UDP, uridine diphosphate. Modified from Winn and Wells (1995) with kind permission from Wiley-Blackwell.

bioactivation of proteratogens by embryonic PHSs and LPOs is necessary for the formation of ROS and subsequent macromolecule damage in the developing embryo (Wells et al., 1997). Additionally, embryonic ROS formation and subsequent oxidative stress may be induced by hypoxia. It is well known from adult cases of cardiovascular diseases (Madamanchi et al., 2005) that ROS are extensively formed during reperfusion of ischemic tissues, while there is considerable evidence that hypoxia followed by reperfusion is teratogenic in animal studies (Wellfelt et al., 1999). Besides embryonic ROS generation, maternal determinants are thought to play an indirect role in ROS-mediated teratogenesis. Embryonic exposure to proteratogens is altered by maternal pathways that eliminate these compounds or their metabolites before they can cross the placenta. Deficiencies in those pathways increase the maternal plasma concentration of proteratogens and therefore the amount that reaches the embryo. Furthermore, maternal production of factors that interfere with embryonic ROS-mediated signal transduction or alter embryonic determinants of oxidative stress may also contribute to the risk of teratogenicity (Wells et al., 2005).

Vascular Disruption

Vascular disruption defects are structural birth defects resulting from interference with or extrinsic breakdown of an originally normal prenatal development of the arteries, veins and capillaries (vasculature) (Spranger et al., 1982; Gilbert-Barness and Van Allen, 2007). Traditionally, it has been stressed that a teratogen exerts its influence on the fetus during the first 3 months of development. Prenatal exposure to agents which can induce vascular disruption, however, can also induce damage later in pregnancy to structures that were initially formed normally. After birth it may be impossible to determine whether a certain structural anomaly, such as a limb defect, is the result of an intrinsically abnormal developmental process, vascular disturbances or, for example, amniotic banding.

Vascular disruption refers to disturbances in the blood circulation in the uterine-placental unit, the placental-fetal unit or the fetus itself. These disturbances include hyperperfusion, hypoperfusion, hypoxia and obstruction. They may be caused by acute or chronic decreases in uterine blood flow, vascular infections or an abnormal anatomy in the uterine-placental unit. Factors such as placental insufficiency, amnion rupture and umbilical cord obstruction may cause failures in the vascular supply in the placental-fetal unit. In the fetus, disruption of newly formed vessels, external compression, embolic events, premature regression of embryonic vessels, occlusion with venous engorgement and abnormal regulation of vessel formation lead to vascular disruption (Van Allen, 1992). Vasoconstriction of maternal and fetal vessels, hypoperfusion and obstruction may cause a reduced supply of nutrients to the embryonic tissues, which can affect development and growth of embryonic structures or result in tissue loss. The latter may result in a phenotype similar to a primary malformation (Hootnick et al., 1980). Furthermore, these disturbances may create a state of hypoxia, which is involved in the formation of ROS and oxidative stress (Ornoy, 2007).

Exposure to vasoactive substances in pregnancy, especially to those with vasoconstrictive effects, have been hypothesized to play a causal role in vascular disruption defects. These teratogens could decrease placental or fetal blood flow or affect the development of blood vessels, thereby changing the structure and/or anatomy of the vasculature (Gilbert-Barness and Van Allen, 2007). In epidemiologic studies, vasoactive therapeutic drugs that have reported associations with the vascular disruption defects described below include misoprostol (Orioli and Castilla, 2000; Vargas et al., 2000), aspirin (Kozer et al., 2002; Werler et al., 2002), ergotamine (Raymond, 1995; Smets et al., 2004) and pseudoephedrine (Werler et al., 2002; Werler et al., 2004). However, all drugs with vasoconstrictive or vasodilating effects may have the potential to cause birth defects due to vascular disruption.

The types of structural anomalies that may be caused by vascular disruption are determined by the timing during gestation, the location and severity of tissue damage and the possible presence of secondary adhesion of necrotic tissue with adjacent organs or the amnion (Gilbert-Barness and Van Allen, 2007). During embryogenesis, vascular disruption results in aberrant differentiation and distortion of contiguous tissues, loss of tissue and incomplete development of structures within the same or a secondary embryonic developmental field. Anomalies resulting from vascular disruption during the fetal period are usually limited to the areas with disturbed blood supply, to which the peripheral vasculature is most susceptible (Van Allen, 1992). Therefore, the majority of defects caused by tissue damage through vascular disruption occur in structures supplied by the most peripheral vasculature, such as the distal limbs and the embryonic intestine (Jones, 1991; Los et al., 1999). Birth defects that were attributed to vascular disruption include terminal limb reductions (Kino, 1975; Hoyme et al., 1982), hydranencephaly/porencephaly (Hoyme et al., 1981a; Mittelbronn et al., 2006), gastroschisis (Hoyme et al., 1981b; Komuro et al., 2003), small intestinal atresia (Louw and Barnard, 1955; Cragan et al., 1994) and Poland anomaly (Shalev and Hall, 2003; Puvabanditsin et al., 2005). However, there are no known experimental models for the complete range of birth defects caused by vascular disruption. The majority of evidence in support of this mechanism comes from case reports with suspected vascular events such as occlusion, emboli, amnion rupture and twin placental vessel anastomoses (Gilbert-Barness and Van Allen, 2007).

Specific Receptor- or Enzyme-mediated Teratogenesis

Many medical drugs act on a specific receptor or enzyme in the human body, leading to a particular mechanism of action. Below we describe the possible effects of inhibition or stimulation of some of these specific receptors and enzymes on fetal development.

Angiotensin-converting enzyme and angiotensin II receptors

The renin–angiotensin system (Fig. 3) is generally described as a hormonal system that plays an important role in the regulation of blood pressure and in the homeostasis of extracellular fluid volume. The main effector hormone of this system is angiotensin II (AT II), which elevates blood pressure by acting directly on vascular smooth muscle cells to cause vasoconstriction. The components of the renin–angiotensin system are present in the human fetus, although their distribution varies compared with that in adults (Schütz et al.,

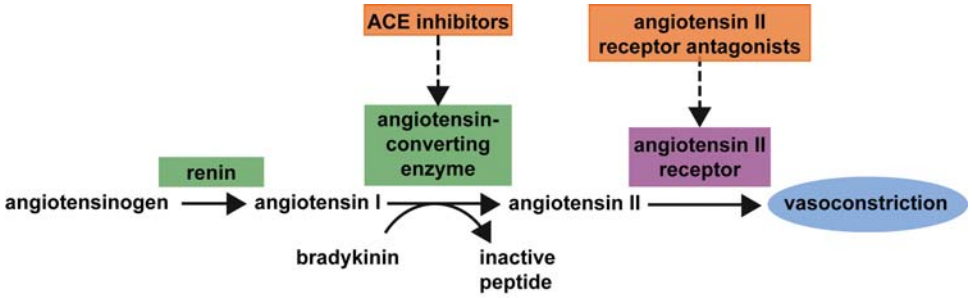

Figure 3 The renin–angiotensin system. ACE, angiotensin-converting enzyme.

1996). Two types of commonly used antihypertensive drugs, the angiotensin-converting enzyme (ACE) inhibitors and the AT II receptor antagonists, may disrupt the fetal renin–angiotensin system and thereby impair fetal development. In contrast to other antihypertensive drugs, ACE inhibitors and AT II receptor antagonists also influence renal function (Jackson and Garrison, 1996). Therefore, their effects are not exclusively produced through fetal hypotension and vascular disruption. The decrease in fetal renal vascular tone may contribute to a human malformation syndrome that is typical for exposure to ACE inhibitors during the second and third trimesters of pregnancy, characterized by renal tubular dysgenesis and oligohydramnios, their sequelae, including limb contractures and pulmonary hypoplasia, and hypocalvaria (Pryde *et al.*, 1993; Shotan *et al.*, 1994). Although the two AT II receptor subtypes, AT_1 and AT_2, are expressed in early development (Schütz *et al.*, 1996), the developmental effects of ACE inhibitors during the first trimester are controversial. However, a recent study showed an increased risk of cardiovascular and central nervous system malformations (Cooper *et al.*, 2006). The effects of the less often studied AT II receptor inhibitors are considered to be similar to those of ACE inhibitors.

Hydroxymethylglutaryl-coenzyme A reductase

The mevalonate pathway is a complex pathway with cholesterol as an essential product. In embryonic tissues, cholesterol is needed for normal growth patterns, signaling domains in plasma membranes, synthesis of steroid hormones and activation of Hedgehog morphogens (Carr *et al.*, 1980; Kelley and Herman, 2001). Since Hedgehog proteins act as key regulators of embryonic growth, patterning and morphogenesis of many structures, down-regulation of the synthesis of these proteins may lead to birth defects (Helms *et al.*, 1997; Gofflot *et al.*, 2003). Statins inhibit hydroxymethylglutaryl-coenzyme A (HMG-CoA) reductase, the rate-limiting enzyme in the mevalonate pathway which converts HMG-CoA to mevalonic acid. Therefore, inhibition of this pathway by statins may lead to a wide range of defects. However, epidemiologic studies with appropriate control populations to confirm a statin syndrome in humans have not been performed yet due to the low frequency of statin use among pregnant women. Although a recurrent pattern of structural defects has been described (Edison and Muenke, 2004), a recent study could not confirm this hypothesized pattern (Petersen *et al.*, 2008).

Histone deacetylase

Histone deacetylases (HDACs) are present in most organisms, in which their best known function is the deacetylation of histones. These are crucial in a number of cellular functions, including the regulation of gene expression by chromatin remodelling. HDACs deacetylate lysine residues on histone tails and condensate chromatin, resulting in limited access of transcriptional activators to the DNA (Johnstone, 2002). Therefore, inhibition of HDACs may result in interruption of cell proliferation, differentiation and apoptosis (Marks *et al.*, 2000), which has been shown in cultured tumor cells (Medina *et al.*, 1997; Glick *et al.*, 1999). Although normal cells seem to be relatively resistant to HDAC inhibitors (Qiu *et al.*, 2000; Burgess *et al.*, 2004), HDAC activity is crucial for embryonic development as is shown by the HDAC1 knockout mice, which die early in development due to growth retardation and proliferation defects (Lagger *et al.*, 2002). Not much has been published on the effects of HDAC inhibition in the pathogenesis of human birth defects, but animal studies show that it might lead to axial skeletal malformations (Menegola *et al.*, 2005; Di Renzo *et al.*, 2007) and neural tube defects (Eikel *et al.*, 2006). Drugs that inhibit HDACs include valproic acid (Göttlicher *et al.*, 2001; Phiel *et al.*, 2001), trichostatin A (Yoshida *et al.*, 1990) and salicylates (Di Renzo *et al.*, 2008). Furthermore, boric acid, an inactive ingredient used in pharmaceutical preparations and as an antibacterial product in non-prescription products, may induce hyperacetylation in somites (Di Renzo *et al.*, 2007).

Cyclooxygenase-1

Non-steroidal anti-inflammatory drugs (NSAIDs) are used for their analgesic, antipyretic and anti-inflammatory effects induced by acting as an inhibitor of cyclooxygenases (COXs), which catalyze the conversion of arachidonic acid to prostaglandins. Two distinct isoforms have been identified, COX-1 and COX-2. The constitutive form, COX-1, is expressed in most tissues, where it produces prostaglandins that are necessary for various physiologic processes, such as blood pressure regulation and platelet aggregation. COX-2 expression, on the other hand, is induced by inflammatory mediators, producing prostaglandins which are important in inflammation (Vane *et al.*, 1998). The anti-inflammatory properties of NSAIDs are due to the inhibition of COX-2, whereas the adverse effects of non-selective NSAIDs, which inhibit both COX isoforms, are the result of COX-1 inhibition (Vane *et al.*, 1998). COX-1 inhibition may be involved in the induction

of cardiac, midline and diaphragm defects by non-selective NSAIDs, since these defects were associated with exposure to drugs with a relatively high COX-1/COX-2 ratio in rats and rabbits (Cappon et al., 2003). Furthermore, COX-2 is not expressed during embryogenesis in rats (Stanfield et al., 2003; Streck et al., 2003), which strongly suggests that COX-2 does not play a role in NSAID-induced teratogenicity noted in this species. Acetylsalicylic acid (aspirin), the only NSAID that irreversibly inhibits COX by acetylation (Vane et al., 1998), seems to be associated with a higher incidence of malformations than other NSAIDs in animal studies (Cook et al., 2003). Initially, first trimester exposure to NSAIDs did not seem to be associated with birth defects in humans (Nielsen et al., 2001; Cleves et al., 2004), but recent epidemiologic studies indicate an increased risk of orofacial clefts and cardiovascular defects, especially cardiac septal defects (Ericson and Källén, 2001; Källén and Otterblad Olausson, 2003; Ofori et al., 2006).

N-methyl-D-aspartate receptors

In the developing brain, *N*-methyl-D-aspartate (NMDA) receptors appear to play an important role in neuronal migration and in the formation and elimination of synapses (Komuro and Rakic, 1993). Blockade of the NMDA receptor in studies using NMDA receptor antagonists or knockout mice affect neuronal development (Komuro and Rakic, 1993; Elberger and Deng, 2003), which may result in structural abnormalities of the brain due to errors in migration of neuronal and glial elements (Clarren et al., 1978). Rats are most vulnerable to the effects of NMDA receptor antagonists in the first week after birth (Ikonomidou et al., 1999), during which the expression of NMDA receptors peaks (Monyer et al., 1994) and the brain growth spurt occurs (Dobbing and Sands, 1971). Since the expression of NMDA in humans peaks in weeks 20–22 of gestation (Lee and Choi, 1992), during which the brain growth spurt starts, and continues throughout the third trimester and postnatally (Dobbing and Sands, 1973), it has been hypothesized that humans might be susceptible to the effects of NMDA receptor antagonists from 20 weeks of gestation onward (Ikonomidou et al., 1999). Therefore, it may be concluded that exposure to NMDA receptor antagonists, such as amantadine (Kornhuber et al., 1991), dextromethorphan (Wong et al., 1988) and ketamine (Anis et al., 1983), could result in minor malformations of the brain. Controversial is the suggested role of NMDA receptor antagonists in the induction of neural tube and neural crest defects, as shown by Andaloro et al. (1998) using chick embryos. These results could not be replicated in mice (Bennett et al., 2006) and the widely used drug dextromethorphan does not seem to be associated with congenital defects in humans (Briggs et al., 2008). Although NMDA receptors are being expressed in the human spinal cord during the first trimester (Åkesson et al., 2000), inhibition of these receptors does not appear to play a role in the induction of neural tube and neural crest defects. Therefore, it is questionable whether this mechanism produces major structural birth defects in humans.

5-Hydroxytryptamine receptors and transporters

Serotonin (5-hydroxytryptamine, 5-HT) is a monoamine neurotransmitter, which is derived from the maternal circulation and transported to the embryo (Yavarone et al., 1993a). It is involved in a wide range of processes during development, including morphogenesis of craniofacial structures (Shuey et al., 1993), cranial neural crest migration (Moiseiwitsch and Lauder, 1995) and cell proliferation (Lauder, 1993). The effects of 5-HT appear to be mediated by 5-HT receptors (Choi et al., 1997), G-protein-linked transmembrane receptors with the exception of the 5-HT_3 receptor, which is a ligand-gated ion channel. At least some of the 5-HT receptor subtypes are expressed in mice embryos, and these are shown to be involved in the morphogenesis of various embryonic tissues (Lauder et al., 2000; Nebigil et al., 2001). Therefore, increased stimulation or suppression of 5-HT receptors by agonists and antagonists may cause birth defects. Drugs known to be agonists of some 5-HT receptor subtypes include sumatriptan (Scott, 1994) and buspirone (Tunnicliff, 1991), whereas, among others, risperidone (Schotte et al., 1996), granisetron (Blower, 2003) and quetiapine (Meltzer et al., 2003) antagonize some 5-HT receptor subtypes. Furthermore, the actions of 5-HT are terminated by the uptake of the neurotransmitter by serotonin transporters, implying that prenatal exposure to selective serotonin-reuptake inhibitors (SSRIs) may also cause birth defects. This class of antidepressants, which includes fluoxetine, paroxetine and sertraline, has been shown to cause craniofacial malformations in mice (Shuey et al., 1992). 5-HT also seems to be involved in cardiac morphogenesis (Yavarone et al., 1993b; Sari and Zhou, 2003), indicating that blockade of 5-HT uptake might produce cardiovascular malformations as well. In humans, however, the risk of birth defects associated with SSRIs as a group appears to be small (Kulin et al., 1998; Alwan et al., 2007; Louik et al., 2007), although recent reports suggest an association between paroxetine use and birth defects (Bérard et al., 2007; Källén and Otterblad Olausson, 2007), but this has been refuted by others (Einarson et al., 2008). An association between first-trimester exposure to fluoxetine and cardiovascular anomalies has been suggested as well (Diav-Citrin et al., 2008). Therefore, it may be hypothesized that individual SSRIs may have different effects on the developing embryo. Due to the inconsistencies in the results of epidemiologic studies, one may suspect that other issues also play a role in this possible association, including disease status of the mother and other confounding factors, such as detection bias and use of concomitant medications.

γ-Aminobutyric acid receptors

In vertebrates, γ-aminobutyric acid (GABA) is the major inhibitory neurotransmitter, which binds to specific transmembrane GABA receptors. Extraneuronal GABA-ergic systems are thought to be present in other tissues as well, including the testis (Tillakaratne et al., 1992), oviduct and ovary (Erdö et al., 1989; Tillakaratne et al., 1992) and pancreas (Baekkeskov et al., 1990), where GABA is hypothesized to play a morphogenetic role during embryonic development (Varju et al., 2001). The extraneuronal GABA-ergic system also seems to play an important role in the normal development of the palate (Hagiwara et al., 2003), but the exact function of this system in non-neural tissues is still unknown. The major groups of drugs that exert their pharmacologic actions through GABA receptors are benzodiazepines, which enhance the effects of GABA (Haefely, 1984). Although these drugs are commonly used during pregnancy and neonatal complications such as the 'floppy infant syndrome' and

the 'withdrawal syndrome' have frequently been observed data on the teratogenicity of benzodiazepines are scarce and inconsistent. In some epidemiologic studies, use of benzodiazepines in the first trimester has been associated with orofacial clefts (Dolovich *et al.*, 1998), cardiovascular malformations (Czeizel *et al.*, 2004) and gastrointestinal tract atresia (Norstedt Wikner *et al.*, 2007), but other studies did not find an association with birth defects (Rosenberg *et al.*, 1983; Ornoy *et al.*, 1998; Lin *et al.*, 2004).

Carbonic anhydrase

Carbonic anhydrases are metalloenzymes that catalyze the reversible hydration of CO_2 into the bicarbonate ion and protons. This reaction is involved in many biological processes, including pH homeostasis, respiration, biosynthetic reactions and bone resorption (Maren, 1967; Sly and Hu, 1995). Several cytoplasmic and membrane-bound carbonic anhydrase isoenzymes are expressed in various tissues in developing human and mouse embryos (Jeffery *et al.*, 1980; Lönnerholm and Wistrand, 1983; Kallio *et al.*, 2006), and inhibitors of carbonic anhydrase, such as acetazolamide, which is used in the treatment of epilepsy, altitude sickness, edema and sleep apnea, have been associated with birth defects, especially limb deformities (Layton and Hallesy, 1965; Scott *et al.*, 1990). A reduction in embryonic intracellular pH is thought to be the teratogenic mechanism of carbonic anhydrase inhibitors (Scott *et al.*, 1990). Intracellular pH has been shown to control or to be associated with various cellular functions, including protein synthesis, proliferation and glycolysis (Madshus, 1988). Interference with these processes may result in abnormal development, but evidence of the existence of this mechanism in humans is lacking.

Summary

From the literature, we identified six principal teratogenic mechanisms associated with medical drug use. Beside the fact that almost all medical drugs classified by Schwarz *et al.* (2007) as U.S. FDA class X are associated with at least one of these mechanisms, various other prescription and over the counter drugs may produce teratogenic effects through these mechanisms. Increased risks for specific birth defects have been observed for some medical drugs after use in human pregnancy, which strengthens the evidence in favor of the associated teratogenic mechanisms. However, since the possibilities to conduct experiments during human pregnancy are very limited, the major part of the evidence in support of various mechanisms described above was derived from animal studies, in which the dosages administered were often far above the therapeutic dosage schedules used in humans. Therefore, we cannot be sure that these mechanisms also apply to humans. In addition, some mechanisms share similar pathways and some drugs may be involved in multiple mechanisms, e.g. valproic acid. Nevertheless, the identification of teratogenic mechanisms are critical for research purposes, in particular for observational studies, in which specific medications with a similar teratogenic mechanism might be combined to increase study power. It may have implications for drug development and for prescribing multiple drugs to women of reproductive age as well, especially since combinations of seemingly unrelated drugs may produce specific teratogenic mechanisms, which may strongly increase the risk of birth defects. Given that discontinuing a certain medication may pose even a higher risk for severe complications than continuing with the use of a possible teratogen, the benefits for the mother should always be balanced against the risks for the (unborn) child when prescribing drug treatment to pregnant women.

Authors' Roles

M.v.G.: lead author, responsible for study design, literature search, data interpretation, preparation of draft manuscript. I.v.R.: study design, data interpretation, critical review manuscript. R.M.: agreed study design, data interpretation, critical review manuscript. G.Z.: agreed study design, data interpretation, critical review manuscript. L.d.J.v.d.B.: agreed study design, data interpretation, critical review manuscript. N.R.: study design, supervised literature search, data interpretation, critical review manuscript.

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References

Adham IM, Agoulnik AI. Insulin-like 3 signalling in testicular descent. *Int J Androl* 2004;**27**:257–265.

Åkesson E, Kjældgaard A, Samuelsson EB, Seiger A, Sundström E. Ionotropic glutamate receptor expression in human spinal cord during first trimester development. *Brain Res Dev Brain Res* 2000;**119**:55–63.

Alwan S, Reefhuis J, Rasmussen SA, Olney RS, Friedman JM. Use of selective serotonin-reuptake inhibitors in pregnancy and the risk of birth defects. *N Engl J Med* 2007;**356**:2684–2692.

Andaloro VJ, Monaghan DT, Rosenquist TH. Dextromethorphan and other *N*-methyl-D-aspartate receptor antagonists are teratogenic in the avian embryo model. *Pediatr Res* 1998;**43**:1–7.

Anis NA, Berry SC, Burton NR, Lodge D. The dissociative anaesthetics, ketamine and phencyclidine, selectively reduce excitation of central mammalian neurones by *N*-methyl-aspartate. *Br J Pharmacol* 1983; **79**:565–575.

Antony AC. The biological chemistry of folate receptors. *Blood* 1992; **79**:2807–2820.

Baekkeskov S, Aanstoot HJ, Christgau S, Reetz A, Solimena M, Cascalho M, Folli F, Richter-Olesen H, De Camilli P. Identification of the 64K autoantigen in insulin-dependent diabetes as the GABA-synthesizing enzyme glutamic acid decarboxylase. *Nature* 1990; **347**:151–156.

Bakker MK, Jentink J, Vroom F, van den Berg PB, de Walle HEK, de Jong-van den Berg LTW. Drug prescription patterns before, during and after pregnancy for chronic, occasional and pregnancy-related drugs in the Netherlands. *BJOG* 2006;**113**:559–568.

Bennett GD, VanWaes J, Moser K, Chaudoin T, Starr L, Rosenquist TH. Failure of homocysteine to induce neural tube defects in a mouse model. *Birth Defects Res B Dev Reprod Toxicol* 2006;**77**:89–94.

Bérard A, Ramos E, Rey E, Blais L, St André M, Oraichi D. First trimester exposure to paroxetine and risk of cardiac malformations in infants: the importance of dosage. *Birth Defects Res B Dev Reprod Toxicol* 2007; **80**:18–27.

Blom HJ, Shaw GM, den Heijer M, Finnell RH. Neural tube defects and folate: case far from closed. *Nat Rev Neurosci* 2006;**7**:724–731.

Blower PR. Granisetron: relating pharmacology to clinical efficacy. *Support Care Cancer* 2003;**11**:93–100.

Bockman DE, Kirby ML. Dependence of thymus development on derivatives of the neural crest. *Science* 1984;**223**:498–500.

Botto LD, Yang Q. 5,10-Methylenetetrahydrofolate reductase gene variants and congenital anomalies: a HuGE review. *Am J Epidemiol* 2000;**151**:862–877.

Briggs GG, Freeman RK, Yaffe SJ. Dextromethorphan. In Briggs GG, Freeman RK, Yaffe SJ (eds). *Drugs in Pregnancy and Lactation*. Philadelphia: Lippincott, Williams & Wilkins, 2008, 506–510.

Brouwer IA, van Dusseldorp M, West CE, Meyboom S, Thomas CMG, Duran M, van het Hof KH, Eskes TKAB, Hautvast JGAJ, Steegers-Theunissen RPM. Dietary folate from vegetables and citrus fruit decreases plasma homocysteine concentrations in humans in a dietary controlled trial. *J Nutr* 1999;**129**:1135–1139.

Brouwers MM, Feitz WFJ, Roelofs LAJ, Kiemeney LALM, de Gier RPE, Roeleveld N. Hypospadias: a transgenerational effect of diethylstilbestrol? *Hum Reprod* 2006;**21**:666–669.

Burgess A, Ruefli A, Beamish H, Warrener R, Saunders N, Johnstone R, Gabrielli B. Histone deacetylase inhibitors specifically kill nonproliferating tumour cells. *Oncogene* 2004;**23**:6693–6701.

Candito M, Rivet R, Herbeth B, Boisson C, Rudigoz RC, Luton D, Journel H, Oury JF, Roux F, Saura R *et al*. Nutritional and genetic determinants of vitamin B and homocysteine metabolisms in neural tube defects: a multicenter case–control study. *Am J Med Genet A* 2008;**146**:1128–1133.

Cappon GD, Cook JC, Hurtt ME. Relationship between cyclooxygenase 1 and 2 selective inhibitors and fetal development when administered to rats and rabbits during the sensitive periods for heart development and midline closure. *Birth Defects Res B Dev Reprod Toxicol* 2003; **68**:47–56.

Carr BR, Parker CR Jr, Milewich L, Porter JC, MacDonald PC, Simpson ER. The role of low density, high density, and very low density lipoproteins in steroidogenesis by the human fetal adrenal gland. *Endocrinology* 1980; **106**:1854–1860.

Cederroth CR, Schaad O, Descombes P, Chambon P, Vassalli JD, Nef S. Estrogen receptor α is a major contributor to estrogen-mediated fetal testis dysgenesis and cryptorchidism. *Endocrinology* 2007; **148**:5507–5519.

Chai Y, Maxson RE Jr. Recent advances in craniofacial morphogenesis. *Dev Dynam* 2006;**235**:2353–2375.

Choi DS, Ward SJ, Messaddeq N, Launay JM, Maroteaux L. 5-HT2B receptor-mediated serotonin morphogenetic functions in mouse cranial neural crest and myocardiac cells. *Development* 1997;**124**:1745–1755.

Christiansen S, Scholze M, Axelstad M, Boberg J, Kortenkamp A, Hass U. Combined exposure to anti-androgens causes markedly increased frequencies of hypospadias in the rat. *Int J Androl* 2008;**31**:241–248.

Clarren SK, Alvord EC Jr, Sumi SM, Streissguth AP, Smith DW. Brain malformations related to prenatal exposure to ethanol. *J Pediatr* 1978; **92**:64–67.

Cleves MA, Savell VH Jr, Raj S, Zhao W, Correa A, Werler MM, Hobbs CA. Maternal use of acetaminophen and nonsteroidal anti-inflammatory drugs (NSAIDs), and muscular ventricular septal defects. *Birth Defects Res A Clin Mol Teratol* 2004;**70**:107–113.

Clouthier DE, Hosoda K, Richardson JA, Williams SC, Yanagisawa H, Kuwaki T, Kumada M, Hammer RE, Yanagisawa M. Cranial and cardiac neural crest defects in endothelin-A receptor-deficient mice. *Development* 1998;**125**:813–824.

Clozel M, Breu V, Gray GA, Kalina B, Löffler BM, Burri K, Cassal JM, Hirth G, Müller M, Neidhart W *et al*. Pharmacological characterization of bosentan, a new potent orally active nonpeptide endothelin receptor antagonist. *J Pharmacol Exp Ther* 1994;**270**:228–235.

Coelho CND, Klein NW. Methionine and neural tube closure in cultured rat embryos: morphological and biochemical analyses. *Teratology* 1990; **42**:437–451.

Cook JC, Jacobson CF, Gao F, Tassinari MS, Hurtt ME, DeSesso JM. Analysis of the nonsteroidal anti-inflammatory drug literature for potential developmental toxicity in rats and rabbits. *Birth Defects Res B Dev Reprod Toxicol* 2003;**68**:5–26.

Cooper WO, Hernandez-Diaz S, Arbogast PG, Dudley JA, Dyer S, Gideon PS, Hall K, Ray WA. Major congenital malformations after first-trimester exposure to ACE inhibitors. *N Engl J Med* 2006; **354**:2443–2451.

Cragan JD, Martin ML, Waters GD, Khoury MJ. Increased risk of small intestinal atresia among twins in the United States. *Arch Pediatr Adolesc Med* 1994;**148**:733–739.

Crescioli C, Maggi M, Vannelli GB, Ferruzzi P, Granchi S, Mancina R, Muratori M, Forti G, Serio M, Luconi M. Expression of functional estrogen receptors in human fetal male external genitalia. *J Clin Endocrinol Metab* 2003;**88**:1815–1824.

Czeizel AE. Prevention of congenital abnormalities by periconceptional multivitamin supplementation. *Br Med J* 1993;**306**:1645–1648.

Czeizel AE, Rockenbauer M, Sørensen HT, Olsen J. A population-based case–control study of oral chlordiazepoxide use during pregnancy and risk of congenital abnormalities. *Neurotoxicol Teratol* 2004;**26**:593–598.

Danielsson BR, Sköld AC, Johansson A, Dillner B, Blomgren B. Teratogenicity by theh ERG potassium channel blocking drug almokalant: use of hypoxia marker gives evidence for a hypoxia-related mechanism mediated via embryonic arrhythmia. *Toxicol Appl Pharmacol* 2003;**193**:168–176.

Defoort EN, Kim PM, Winn LM. Valproic acid increases conservative homologous recombination frequency and reactive oxygen species formation: a potential mechanism for valproic acid-induced neural tube defects. *Mol Pharmacol* 2006;**69**:1304–1310.

Delbès G, Levacher C, Duquenne C, Racine C, Pakarinen P, Habert R. Endogenous estrogens inhibit mouse fetal Leydig cell development via estrogen receptor α. *Endocrinology* 2005;**146**:2454–2461.

Dennery PA. Effects of oxidative stress on embryonic development. *Birth Defects Res C Embryo Today* 2007;**81**:155–162.

Di Renzo F, Cappelletti G, Broccia ML, Giavini E, Menegola E. Boric acid inhibits embryonic histone deacetylases: a suggested mechanism to explain boric acid-related teratogenicity. *Toxicol Appl Pharmacol* 2007; **220**:178–185.

Di Renzo F, Cappelletti G, Broccia ML, Giavini E, Menegola E. The inhibition of embryonic histone deacetylases as the possible mechanism accounting for axial skeletal malformations induced by sodium salicylate. *Toxicol Sci* 2008;**104**:397–404.

Diav-Citrin O, Park YH, Veerasuntharam G, Polachek H, Bologa M, Pastuszak A, Koren G. The safety of mesalamine in human pregnancy: a prospective controlled cohort study. *Gastroenterology* 1998;**114**:23–28.

Diav-Citrin O, Shechtman S, Weinbaum D, Wajnberg R, Avgil M, Di Gianantonio E, Clementi M, Weber-Schoendorfer C, Schaefer C, Ornoy A. Paroxetine and fluoxetine in pregnancy: a prospective, multicentre, controlled, observational study. *Br J Clin Pharmacol* 2008; **66**:695–705.

Dobbing J, Sands J. Vulnerability of developing brain. IX. The effect of nutritional growth retardation on the timing of the brain growth-spurt. *Biol Neonate* 1971;**19**:363–378.

Dobbing J, Sands J. Quantitative growth and development of human brain. *Arch Dis Child* 1973;**48**:757–767.

Dolovich LR, Addis A, Vaillancourt JMR, Power JDB, Koren G, Einarson TR. Benzodiazepine use in pregnancy and major malformations or oral cleft: meta-analysis of cohort and case–control studies. *Br Med J* 1998;**317**:839–843.

Duester G. Families of retinoid dehydrogenases regulating vitamin A function: production of visual pigment and retinoic acid. *Eur J Biochem* 2000;**267**:4315–4324.

Edison RJ, Muenke M. Mechanistic and epidemiologic considerations in the evaluation of adverse birth outcomes following gestational exposure to statins. *Am J Med Genet A* 2004;**131**:287–298.

Eikel D, Lampen A, Nau H. Teratogenic effects mediated by inhibition of histone deacetylases: evidence from quantitative structure activity relationships of 20 valproic acid derivatives. *Chem Res Toxicol* 2006; **19**:272–278.

Einarson A, Pistelli A, DeSantis M, Malm H, Paulus WD, Panchaud A, Kennedy D, Einarson TR, Koren G. Evaluation of the risk of congenital cardiovascular defects associated with use of paroxetine during pregnancy. *Am J Psychiatry* 2008;**165**:749–752.

Elberger AJ, Deng J. Corpus callosum and visual cortex of mice with deletion of the NMDA-NR1 receptor: I. Accelerated development of callosal projection neurons. *Brain Res Dev Brain Res* 2003; **144**:121–133.

Eling TE, Thompson DC, Foureman GL, Curtis JF, Hughes MF. Prostaglandin H synthase and xenobiotic oxidation. *Annu Rev Pharmacol Toxicol* 1990;**30**:1–45.

Elmazar MMA, Rühl R, Reichert U, Shroot B, Nau H. RARα-mediated teratogenicity in mice is potentiated by an RXR agonist and reduced by an RAR antagonist: dissection of retinoid receptor-induced pathways. *Toxicol Appl Pharmacol* 1997;**146**:21–28.

Emmen JMA, McLuskey A, Adham IM, Engel W, Verhoef-Post M, Themmen APN, Grootegoed JA, Brinkmann AO. Involvement of insulin-like factor 3 (Insl3) in diethylstilbestrol-induced cryptorchidism. *Endocrinology* 2000;**141**:846–849.

Engeland A, Bramness JG, Daltveit AK, Rønning M, Skurtveit S, Furu K. Prescription drug use among fathers and mothers before and during pregnancy. A population-based cohort study of 106 000 pregnancies in Norway 2004–2006. *Br J Clin Pharmacol* 2008;**65**:653–660.

Epstein JA, Li J, Lang D, Chen F, Brown CB, Jin F, Lu MM, Thomas M, Liu ECJ, Wessels A *et al*. Migration of cardiac neural crest cells in *Splotch* embryos. *Development* 2000;**127**:1869–1878.

Erdö SL, Joo F, Wolff JR. Immunohistochemical localization of glutamate decarboxylase in the rat oviduct and ovary: further evidence for non-neural GABA systems. *Cell Tissue Res* 1989;**255**:431–434.

Ericson A, Källén BAJ. Nonsteroidal anti-inflammatory drugs in early pregnancy. *Reprod Toxicol* 2001;**15**:371–375.

Fantel AG, Person RE. Involvement of mitochondria and other free radical sources in normal and abnormal fetal development. *Ann N Y Acad Sci* 2002;**959**:424–433.

Finer LB, Henshaw SK. Disparities in rates of unintended pregnancy in the United States, 1994 and 2001 Perspect Sex. *Reprod Health* 2006; **38**:90–96.

Foster W, Myllynen P, Winn LM, Ornoy A, Miller RK. Reactive oxygen species, diabetes and toxicity in the placenta: a workshop report. *Placenta* 2008;**29**:S105–S107.

Fujii H, Sato T, Kaneko S, Gotoh O, Fujii-Kuriyama Y, Osawa K, Kato S, Hamada H. Metabolic inactivation of retinoic acid by a novel P450 differentially expressed in developing mouse embryos. *EMBO J* 1997; **16**:4163–4173.

Gaskell TL, Robinson LLL, Groome NP, Anderson RA, Saunders PTK. Differential expression of two estrogen receptor β isoforms in the human fetal testis during the second trimester of pregnancy. *J Clin Endocrinol Metab* 2003;**88**:424–432.

Gilbert-Barness E, Van Allen MI. Vascular disruptions. In Gilbert-Barness E, Kapur RP, Siebert JR, Potter EL (eds). *Potter's Pathology of the Fetus, Infant and Child*. Philadelphia, PA: Mosby Elsevier, 2007, 176–212.

Gill SK, O'Brien L, Einarson TR, Koren G. The safety of proton pump inhibitors (PPIs) in pregnancy: a meta-analysis. *Am J Gastroenterol* 2009;**104**:1541–1545.

Giusti RM, Iwamoto K, Hatch EE. Diethylstilbestrol revisited: a review of the long-term health effects. *Ann Intern Med* 1995;**122**:778–788.

Giwercman A, Rylander L, Giwercman YL. Influence of endocrine disruptors on human male fertility. *Reprod Biomed Online* 2007; **15**:633–642.

Glick RD, Swendeman SL, Coffey DC, Rifkind RA, Marks PA, Richon VM, La Quaglia MP. Hybrid polar histone deacetylase inhibitor induces apoptosis and CD95/CD95 ligand expression in human neuroblastoma. *Cancer Res* 1999;**59**:4392–4399.

Gofflot F, Hars C, Illien F, Chevy F, Wolf C, Picard JJ, Roux C. Molecular mechanisms underlying limb anomalies associated with cholesterol deficiency during gestation: implications of Hedgehog signaling. *Hum Mol Genet* 2003;**12**:1187–1198.

Göttlicher M, Minucci S, Zhu P, Krämer OH, Schimpf A, Giavara S, Sleeman JP, Lo Coco F, Nervi C, Pelicci PG *et al*. Valproic acid defines a novel class of HDAC inhibitors inducing differentiation of transformed cells. *EMBO J* 2001;**20**:6969–6978.

Haefely W. Benzodiazepine interactions with GABA receptors. *Neurosci Lett* 1984;**47**:201–206.

Hagiwara N, Katarova Z, Siracusa LD, Brilliant MH. Nonneuronal expression of the $GABA_A$ ß3 subunit gene is required for normal palate development in mice. *Dev Biol* 2003;**254**:93–101.

Hansen JM. Oxidative stress as a mechanism of teratogenesis. *Birth Defects Res C Embryo Today* 2006;**78**:293–307.

Hansen JM, Harris C. A novel hypothesis for thalidomide-induced limb teratogenesis: redox misregulation of the NF-κB pathway. *Antioxid Redox Signal* 2004;**6**:1–14.

Hauser R, Duty S, Godfrey-Bailey L, Calafat AM. Medications as a source of human exposure to phthalates. *Environ Health Perspect* 2004; **112**:751–753.

Helms JA, Kim CH, Hu D, Minkoff R, Thaller C, Eichele G. *Sonic hedgehog* participates in craniofacial morphogenesis and is down-regulated by teratogenic doses of retinoic acid. *Dev Biol* 1997;**187**:25–35.

Henry EC, Miller RK, Baggs RB. Direct fetal injections of diethylstilbestrol and 17β-estradiol: a method for investigating their teratogenicity. *Teratology* 1984;**29**:297–304.

Herbst AL, Ulfelder H, Poskanzer DC. Adenocarcinoma of the vagina: association of maternal stilbestrol therapy with tumor appearance in young women. *N Engl J Med* 1971;**284**:878–881.

Hernández-Díaz S, Werler MM, Walker AM, Mitchell AA. Folic acid antagonists during pregnancy and the risk of birth defects. *N Engl J Med* 2000;**343**:1608–1614.

Hernández-Díaz S, Werler MM, Walker AM, Mitchell AA. Neural tube defects in relation to use of folic acid antagonists during pregnancy. *Am J Epidemiol* 2001;**153**:961–968.

Hernández-Díaz S, Mitchell AA, Kelley KE, Calafat AM, Hauser R. Medications as a potential source of exposure to phthalates in the U.S. population. *Environ Health Perspect* 2009;**117**:185–189.

Hodgert Jury H, Zacharewski TR, Hammond GL. Interactions between human plasma sex hormone-binding globulin and xenobiotic ligands. *J Steroid Biochem Mol Biol* 2000;**75**:167–176.

Hootnick DR, Levinsohn EM, Randall PA, Packard DS Jr. Vascular dysgenesis associated with skeletal dysplasia of the lower limb. *J Bone Joint Surg Am* 1980;**62**:1123–1129.

Hoyme HE, Higginbottom MC, Jones KL. Vascular etiology of disruptive structural defects in monozygotic twins. *Pediatrics* 1981a;**67**:288–291.

Hoyme HE, Higginbottom MC, Jones KL. The vascular pathogenesis of gastroschisis: intrauterine interruption of the omphalomesenteric artery. *J Pediatr* 1981b;**98**:228–231.

Hoyme HE, Jones KL, Van Allen MI, Saunders BS, Benirschke K. Vascular pathogenesis of transverse limb reduction defects. *J Pediatr* 1982; **101**:839–843.

Hutson JM, Hasthorpe S, Heyns CF. Anatomical and functional aspects of testicular descent and cryptorchidism. *Endocr Rev* 1997;**18**:259–280.

Ikonomidou C, Bosch F, Miksa M, Bittigau P, Vöckler J, Dikranian K, Tenkova TI, Stefovska V, Turski L, Olney JW. Blockade of NMDA receptors and apoptotic neurodegeneration in the developing brain. *Science* 1999;**283**:70–74.

Ishibashi M, Akazawa S, Sakamaki H, Matsumoto K, Yamasaki H, Yamaguchi Y, Goto S, Urata Y, Kondo T, Nagataki S. Oxygen-induced embryopathy and the significance of glutathione-dependent antioxidant system in the rat embryo during early organogenesis. *Free Radic Biol Med* 1997;**22**:447–454.

Jackson EK, Garrison JC. Renin and angiotensin. In Hardman JG, Limbird LE (eds). *Goodman & Gilman's the Pharmacological Basis of Therapeutics*. New York: McGraw-Hill, 1996, 733–758.

Jeffery S, Edwards Y, Carter N. Distribution of CAIII in fetal and adult human tissue. *Biochem Genet* 1980;**18**:843–849.

Johnstone RW. Histone-deacetylase inhibitors: novel drugs for the treatment of cancer. *Nat Rev Drug Discov* 2002;**1**:287–299.

Jones KL. Developmental pathogenesis of defects associated with prenatal cocaine exposure: fetal vascular disruption. *Clin Perinatol* 1991; **18**:139–146.

Jordan RL, Wilson JG, Schumacher HJ. Embryotoxicity of the folate antagonist methotrexate in rats and rabbits. *Teratology* 1977;**15**:73–79.

Josso N, di Clemente N, Gouédard L. Anti-Müllerian hormone and its receptors. *Mol Cell Endocrinol* 2001;**179**:25–32.

Juchau MR, Lee QP, Fantel AG. Xenobiotic biotransformation/ bioactivation in organogenesis-stage conceptual tissues: implications for embryotoxicity and teratogenesis. *Drug Metab Rev* 1992; **24**:195–238.

Källén BAJ, Otterblad Olausson P. Maternal drug use in early pregnancy and infant cardiovascular defect. *Reprod Toxicol* 2003;**17**:255–261.

Källén BAJ, Otterblad Olausson P. Maternal use of selective serotonin re-uptake inhibitors in early pregnancy and infant congenital malformations. *Birth Defects Res A Clin Mol Teratol* 2007;**79**:301–308.

Kallio H, Pastorekova S, Pastorek J, Waheed A, Sly WS, Mannisto S, Heikinheimo M, Parkkila S. Expression of carbonic anhydrases IX and XII during mouse embryonic development. *BMC Dev Biol* 2006;**6**:22.

Kappus H. Overview of enzyme systems involved in bio-reduction of drugs and in redox cycling. *Biochem Pharmacol* 1986;**35**:1–6.

Kastner P, Grondona JM, Mark M, Gansmuller A, LeMeur M, Decimo D, Vonesch JL, Dollé P, Chambon P. Genetic analysis of RXRα developmental function: convergence of RXR and RAR signaling pathways in heart and eye morphogenesis. *Cell* 1994;**78**:987–1003.

Kelley RI, Herman GE. Inborn errors of sterol biosynthesis. *Annu Rev Genomics Hum Genet* 2001;**2**:299–341.

Kester MHA, Bulduk S, Tibboel D, Meinl W, Glatt H, Falany CN, Coughtrie MWH, Bergman A, Safe SH, Kuiper GGJM *et al.* Potent inhibition of estrogen sulfotransferase by hydroxylated PCB metabolites: a novel pathway explaining the estrogenic activity of PCBs. *Endocrinology* 2000;**141**:1897–1900.

Kim KS, Torres CR Jr, Yucel S, Raimondo K, Cunha GR, Baskin LS. Induction of hypospadias in a murine model by maternal exposure to synthetic estrogens. *Environ Res* 2004;**94**:267–275.

Kino Y. Clinical and experimental studies of the congenital constriction band syndrome, with an emphasis on its etiology. *J Bone Joint Surg Am* 1975;**57**:636–643.

Kirby ML, Waldo KL. Role of neural crest in congenital heart disease. *Circulation* 1990;**82**:332–340.

Klip H, Verloop J, van Gool JD, Koster META, Burger CW, van Leeuwen FE. Hypospadias in sons of women exposed to diethylstilbestrol *in utero*: a cohort study. *Lancet* 2002;**359**:1102–1107.

Klopper A. The new placental proteins. *Placenta* 1980;**1**:77–89.

Komuro H, Rakic P. Modulation of neuronal migration by NMDA receptors. *Science* 1993;**260**:95–97.

Komuro H, Watanabe M, Matoba K, Kaneko M. Gastroschisis with omphalomesenteric artery remnant, colonic atresia and arthrogryposis multiplex congenita. *Eur J Pediatr Surg* 2003;**13**:334–336.

Kornhuber J, Bormann J, Hübers M, Rusche K, Riederer P. Effects of the 1-amino-adamantanes at the MK-801-binding site of the NMDA-receptor-gated ion channel: a human postmortem brain study. *Eur J Pharmacol* 1991;**206**:297–300.

Kovacic P, Jacintho JD. Reproductive toxins: pervasive theme of oxidative stress and electron transfer. *Curr Med Chem* 2001;**8**:863–892.

Kovacic P, Somanathan R. Mechanism of teratogenesis: electron transfer, reactive oxygen species, and antioxidants. *Birth Defects Res C Embryo Today* 2006;**78**:308–325.

Kozer E, Nikfar S, Costei A, Boskovic R, Nulman I, Koren G. Aspirin consumption during the first trimester of pregnancy and congenital anomalies: a meta-analysis. *Am J Obstet Gynecol* 2002;**187**:1623–1630.

Krumlauf R. *Hox* genes in vertebrate development. *Cell* 1994;**78**:191–201.

Kulin NA, Pastuszak A, Sage SR, Schick-Boschetto B, Spivey G, Feldkamp M, Ormond K, Matsui D, Stein-Schechman AK, Cook L *et al.* Pregnancy outcome following maternal use of the new selective serotonin reuptake inhibitors: a prospective controlled multicenter study. *J Am Med Assoc* 1998;**279**:609–610.

LaBonne C, Bronner-Fraser M. Neural crest induction in Xenopus: evidence for a two-signal model. *Development* 1998;**125**:2403–2414.

Lagger G, O'Carroll D, Rembold M, Khier H, Tischler J, Weitzer G, Schuettengruber B, Hauser C, Brunmeir R, Jenuwein T *et al.* Essential function of histone deacetylase 1 in proliferation control and CDK inhibitor repression. *EMBO J* 2002;**21**:2672–2681.

Lambie DG, Johnson RH. Drugs and folate metabolism. *Drugs* 1985; **30**:145–155.

Lambrot R, Muczynski V, Lécureauil C, Angenard G, Coffigny H, Pairault C, Moison D, Frydman R, Habert R, Rouiller-Fabre V. Phthalates impair germ cell development in the human fetal testis *in vitro* without change in testosterone production. *Environ Health Perspect* 2009;**117**:32–37.

Lammer EJ, Chen DT, Hoar RM, Agnish ND, Benke PJ, Braun JT, Curry CJ, Fernhoff PM, Grix AW Jr, Lott IT *et al.* Retinoic acid embryopathy. *N Engl J Med* 1985;**313**:837–841.

Lander HM. An essential role for free radicals and derived species in signal transduction. *FASEB J* 1997;**11**:118–124.

Larsen WJ. *Human Embryology*, 3rd edn. Philadelphia: Churchill Livingstone, 2001.

Lauder JM. Neurotransmitters as growth regulatory signals: role of receptors and second messengers. *Trends Neurosci* 1993;**16**:233–240.

Lauder JM, Wilkie MB, Wu C, Singh S. Expression of 5-HT_{2A}, 5-HT_{2B} and 5-HT_{2C} receptors in the mouse embryo. *Int J Dev Neurosci* 2000; **18**:653–662.

Layton WM Jr, Hallesy DW. Deformity of forelimb in rats: association with high doses of acetazolamide. *Science* 1965;**149**:306–308.

Lee H, Choi BH. Density and distribution of excitatory amino acid receptors in the developing human fetal brain: a quantitative autoradiographic study. *Exp Neurol* 1992;**118**:284–290.

Li D, Pickell L, Liu Y, Wu Q, Cohn JS, Rozen R. Maternal methylenetetrahydrofolate reductase deficiency and low dietary folate lead to adverse reproductive outcomes and congenital heart defects in mice. *Am J Clin Nutr* 2005;**82**:188–195.

Lin AE, Peller AJ, Westgate MN, Houde K, Franz A, Holmes LB. Clonazepam use in pregnancy and the risk of malformations. *Birth Defects Res A Clin Mol Teratol* 2004;**70**:534–536.

Liu L, Wells PG. *In vivo* phenytoin-initiated oxidative damage to proteins and lipids in murine maternal hepatic and embryonic tissue organelles: potential molecular targets of chemical teratogenesis. *Toxicol Appl Pharmacol* 1994;**125**:247–255.

Lo WY, Friedman JM. Teratogenicity of recently introduced medications in human pregnancy. *Obstet Gynecol* 2002;**100**:465–473.

Lohnes D, Mark M, Mendelsohn C, Dollé P, Dierich A, Gorry P, Gansmuller A, Chambon P. Function of the retinoic acid receptors (RARs) during development (I). Craniofacial and skeletal abnormalities in RAR double mutants. *Development* 1994;**120**:2723–2748.

Lönnerholm G, Wistrand PJ. Carbonic anhydrase in the human fetal kidney. *Pediatr Res* 1983;**17**:390–397.

Los FJ, Brandenburg H, Niermeijer MF. Vascular disruptive syndromes after exposure to misoprostol or chorionic villus sampling. *Lancet* 1999;**353**:843–844.

Louik C, Lin AE, Werler MM, Hernández-Díaz S, Mitchell AA. First-trimester use of selective serotonin-reuptake inhibitors and the risk of birth defects. *N Engl J Med* 2007;**356**:2675–2683.

Louw JH, Barnard CN. Congenital intestinal atresia: observations on its origin. *Lancet* 1955;**266**:1065–1067.

Lumley J, Watson L, Watson M, Bower C. Periconceptional supplementation with folate and/or multivitamins for preventing neural tube defects. *Cochrane Database Syst Rev* 2001; doi:10.1002/14651858.CD001056.

Madamanchi NR, Vendrov A, Runge MS. Oxidative stress and vascular disease. *Arterioscler Thromb Vasc Biol* 2005;**25**:29–38.

Madshus IH. Regulation of intracellular pH in eukaryotic cells. *Biochem J* 1988;**250**:1–8.

Maren TH. Carbonic anhydrase: chemistry, physiology, and inhibition. *Physiol Rev* 1967;**47**:595–781.

Marks PA, Richon VM, Rifkind RA. Histone deacetylase inhibitors: inducers of differentiation or apoptosis of transformed cells. *J Natl Cancer Inst* 2000;**92**:1210–1216.

Martin OV, Shialis T, Lester JN, Scrimshaw MD, Boobis AR, Voulvoulis N. Testicular dysgenesis syndrome and the estrogen hypothesis: a quantitative meta-analysis. *Environ Health Perspect* 2008;**116**:149–157.

McLachlan JA. Rodent models for perinatal exposure to diethylstilbestrol and their relation to human disease in the male. In Herbst AL, Bern HA (eds). *Developmental Effects of Diethylstilbestrol (DES) in Pregnancy*. New York, NY: Thieme-Stratton, 1981, 148–157.

McMahon DR, Kramer SA, Husmann DA. Antiandrogen induced cryptorchidism in the pig is associated with failed gubernacular regression and epididymal malformations. *J Urol* 1995;**154**:553–557.

Medina V, Edmonds B, Young GP, James R, Appleton S, Zalewski PD. Induction of caspase-3 protease activity and apoptosis by butyrate and trichostatin A (inhibitors of histone deacetylase): dependence on protein synthesis and synergy with a mitochondrial/cytochrome *c*-dependent pathway. *Cancer Res* 1997;**57**:3697–3707.

Meijer WM, de Walle HEK, Kerstjens-Frederikse WS, de Jong-van den Berg LTW. Folic acid sensitive birth defects in association with intrauterine exposure to folic acid antagonists. *Reprod Toxicol* 2005;**20**:203–207.

Meltzer HY, Li Z, Kaneda Y, Ichikawa J. Serotonin receptors: their key role in drugs to treat schizophrenia. *Prog Neuropsychopharmacol Biol Psychiatry* 2003;**27**:1159–1172.

Menegola E, Di Renzo F, Broccia ML, Prudenziati M, Minucci S, Massa V, Giavini E. Inhibition of histone deacetylase activity on specific embryonic tissues as a new mechanism for teratogenicity. *Birth Defects Res B Dev Reprod Toxicol* 2005;**74**:392–398.

Metzler M. The metabolism of diethylstilbestrol. *CRC Crit Rev Biochem* 1981;**10**:171–212.

Miller RK, Heckmann ME, McKenzie RC. Diethylstilbestrol: placental transfer, metabolism, covalent binding and fetal distribution in the Wistar rat. *J Pharmacol Exp Ther* 1982;**220**:358–365.

Mills JL, McPartlin JM, Kirke PN, Lee YJ, Conley MR, Weir DG, Scott JM. Homocysteine metabolism in pregnancies complicated by neural-tube defects. *Lancet* 1995;**345**:149–151.

Mittelbronn M, Beschorner R, Schittenhelm J, Capper D, Goeppert B, Meyermann R, Meyer-Wittkopf M, Mackensen-Haen S. Multiple thromboembolic events in fetofetal transfusion syndrome in triplets contributing to the understanding of pathogenesis of hydranencephaly in combination with polymicrogyria. *Hum Pathol* 2006;**37**:1503–1507.

Moiseiwitsch JRD, Lauder JM. Serotonin regulates mouse cranial neural crest migration. *Proc Natl Acad Sci USA* 1995;**92**:7182–7186.

Molloy AM, Kirke PN, Troendle JF, Burke H, Sutton M, Brody LC, Scott JM, Mills JL. Maternal vitamin B_{12} status and risk of neural tube defects in a population with high neural tube defect prevalence and no folic acid fortification. *Pediatrics* 2009;**123**:917–923.

Monyer H, Burnashev N, Laurie DJ, Sakmann B, Seeburg PH. Developmental and regional expression in the rat brain and functional properties of four NMDA receptors. *Neuron* 1994;**12**:529–540.

Morini F, Cozzi DA, Ilari M, Casati A, Cozzi F. Pattern of cardiovascular anomalies associated with esophageal atresia: support for a caudal pharyngeal arch neurocristopathy. *Pediatr Res* 2001;**50**:565–568.

Morriss-Kay G. Retinoic acid and craniofacial development: molecules and morphogenesis. *Bioessays* 1993;**15**:9–15.

Myers MF, Li S, Correa-Villaseñor A, Li Z, Moore CA, Hong SX, Berry RJ. Folic acid supplementation and risk for imperforate anus in China. *Am J Epidemiol* 2001;**154**:1051–1056.

Mylchreest E, Sar M, Wallace DG, Foster PMD. Fetal testosterone insufficiency and abnormal proliferation of Leydig cells and gonocytes in rats exposed to di(n-butyl) phthalate. *Reprod Toxicol* 2002;**16**:19–28.

Nakagawa S, Takeichi M. Neural crest emigration from the neural tube depends on regulated cadherin expression. *Development* 1998;**125**:2963–2971.

Nebigil CG, Hickel P, Messaddeq N, Vonesch JL, Douchet MP, Monassier L, György K, Matz R, Andriantsitohaina R, Manivet P *et al.* Ablation of serotonin 5-HT_{2B} receptors in mice leads to abnormal cardiac structure and function. *Circulation* 2001;**103**:2973–2979.

Nielsen GL, Sørensen HT, Larsen H, Pedersen L. Risk of adverse birth outcome and miscarriage in pregnant users of non-steroidal anti-inflammatory drugs: population based observational study and case–control study. *Br Med J* 2001;**322**:266–270.

Nishibatake M, Kirby ML, Van Mierop LH. Pathogenesis of persistent truncus arteriosus and dextroposed aorta in the chick embryo after neural crest ablation. *Circulation* 1987;**75**:255–264.

Norstedt Wikner B, Stiller CO, Bergman U, Asker C, Källén B. Use of benzodiazepines and benzodiazepine receptor agonists during pregnancy: neonatal outcome and congenital malformations Pharmacoepidemiol. *Drug Saf* 2007;**16**:1203–1210.

Ofori B, Oraichi D, Blais L, Rey E, Bérard A. Risk of congenital anomalies in pregnant users of non-steroidal anti-inflammatory drugs: a nested case–control study. *Birth Defects Res B Dev Reprod Toxicol* 2006;**77**:268–279.

Olesen C, Steffensen FH, Nielsen GL, de Jong-van den Berg L, Olsen J, Sørensen HT. Drug use in first pregnancy and lactation: a population-based survey among Danish women. *Eur J Clin Pharmacol* 1999;**55**:139–144.

Orioli IM, Castilla EE. Epidemiological assessment of misoprostol teratogenicity. *BJOG* 2000;**107**:519–523.

Ornoy A. Embryonic oxidative stress as a mechanism of teratogenesis with special emphasis on diabetic embryopathy. *Reprod Toxicol* 2007;**24**:31–41.

Ornoy A, Arnon J, Shechtman S, Moerman L, Lukashova I. Is benzodiazepine use during pregnancy really teratogenic? *Reprod Toxicol* 1998;**12**:511–515.

Otten C, Migliazza L, Xia H, Rodriguez JI, Diez-Pardo JA, Tovar JA. Neural crest-derived defects in experimental esophageal atresia. *Pediatr Res* 2000;**47**:178–183.

Parks LG, Ostby JS, Lambright CR, Abbott BD, Klinefelter GR, Barlow NJ, Gray LE Jr. The plasticizer diethylhexyl phthalate induces malformations by decreasing fetal testosterone synthesis during sexual differentiation in the male rat. *Toxicol Sci* 2000;**58**:339–349.

Parle-McDermott A, Kirke PN, Mills JL, Molloy AM, Cox C, O'Leary VB, Pangilinan F, Conley M, Cleary L, Brody LC *et al.* Confirmation of the R653Q polymorphism of the trifunctional C1-synthase enzyme as a maternal risk for neural tube defects in the Irish population. *Eur J Hum Genet* 2006;**14**:768–772.

Parman T, Wells PG. Embryonic prostaglandin H synthase-2 (PHS-2) expression and benzo[*a*]pyrene teratogenicity in PHS-2 knockout mice. *FASEB J* 2002;**16**:1001–1009.

Parman T, Chen G, Wells PG. Free radical intermediates of phenytoin and related teratogens. *J Biol Chem* 1998;**273**:25079–25088.

Petersen EE, Mitchell AA, Carey JC, Werler MM, Louik C, Rasmussen SA. Maternal exposure to statins and risk for birth defects: a case-series approach. *Am J Med Genet A* 2008;**146**:2701–2705.

Phiel CJ, Zhang F, Huang EY, Guenther MG, Lazar MA, Klein PS. Histone deacetylase is a direct target of valproic acid, a potent anticonvulsant, mood stabilizer, and teratogen. *J Biol Chem* 2001;**276**:36734–36741.

Physicians' Desk Reference, 63rd edn. Montvale, NJ: Thomson Reuters, 2009.

Pollard I. Neuropharmacology of drugs and alcohol in mother and fetus. *Semin Fetal Neonatal Med* 2007;**12**:106–113.

Pryde PG, Sedman AB, Nugent CE, Barr M. Angiotensin-converting enzyme inhibitor fetopathy. *J Am Soc Nephrol* 1993;**3**:1575–1582.

Puvabanditsin S, Garrow E, Augustin G, Titapiwatanakul R, Kuniyoshi KM. Poland-Möbius syndrome and cocaine abuse: a relook at vascular etiology. *Pediatr Neurol* 2005;**32**:285–287.

Qiu L, Burgess A, Fairlie DP, Leonard H, Parsons PG, Gabrielli BG. Histone deacetylase inhibitors trigger a G2 checkpoint in normal cells that is defective in tumor cells. *Mol Biol Cell* 2000;**11**:2069–2083.

Ray JG, Wyatt PR, Thompson MD, Vermeulen MJ, Meier C, Wong PY, Farrell SA, Cole DEC. Vitamin B_{12} and the risk of neural tube defects in a folic-acid-fortified population. *Epidemiology* 2007;**18**:362–366.

Raymond GV. Teratogen update: ergot and ergotamine. *Teratology* 1995; **51**:344–347.

Rider CV, Furr J, Wilson VS, Gray LE Jr. A mixture of seven antiandrogens induces reproductive malformations in rats. *Int J Androl* 2008;**31**:249–262.

Rosenberg L, Mitchell AA, Parsells JL, Pashayan H, Louik C, Shapiro S. Lack of relation of oral clefts to diazepam use during pregnancy. *N Engl J Med* 1983;**309**:1282–1285.

Rosenquist TH, Ratashak SA, Selhub J. Homocysteine induces congenital defects of the heart and neural tube: effect of folic acid. *Proc Natl Acad Sci USA* 1996;**93**:15227–15232.

Ryu S, Kohen R, Samuni A, Ornoy A. Nitroxide radicals protect cultured rat embryos and yolk sacs from diabetic-induced damage. *Birth Defects Res A Clin Mol Teratol* 2007;**79**:604–611.

Sahambi SK, Hales BF. Exposure to 5-bromo-2'-deoxyuridine induces oxidative stress and activator protein-1 DNA binding activity in the embryo. *Birth Defects Res A Clin Mol Teratol* 2006;**76**:580–591.

Sari Y, Zhou FC. Serotonin and its transporter on proliferation of fetal heart cells. *Int J Dev Neurosci* 2003;**21**:417–424.

Schaefer C, Peters P, Miller RK. *Drugs During Pregnancy and Lactation. Treatment Options and Risk Assessment*, 2nd edn. London: Academic Press, 2007.

Scholl TO. Iron status during pregnancy: setting the stage for mother and infant. *Am J Clin Nutr* 2005;**81**:1218S–1222S.

Schotte A, Janssen PFM, Gommeren W, Luyten WHML, van Gompel P, Lesage AS, de Loore K, Leysen JE. Risperidone compared with new and reference antipsychotic drugs: *in vitro* and *in vivo* receptor binding. *Psychopharmacology* 1996;**124**:57–73.

Schütz S, Le Moullec JM, Corvol P, Gasc JM. Early expression of all the components of the renin–angiotensin-system in human development. *Am J Pathol* 1996;**149**:2067–2079.

Schwarz EB, Postlethwaite DA, Hung YY, Armstrong MA. Documentation of contraception and pregnancy when prescribing potentially teratogenic medications for reproductive-age women. *Ann Intern Med* 2007; **147**:370–376.

Scott AK. Sumatriptan clinical pharmacokinetics. *Clin Pharmacokinet* 1994; **27**:337–344.

Scott WJ, Duggan CA, Schreiner CM, Collins MD. Reduction of embryonic intracellular pH: a potential mechanism of acetazolamide-induced limb malformations. *Toxicol Appl Pharmacol* 1990;**103**:238–254.

Shalev SA, Hall JG. Poland anomaly: report of an unusual family. *Am J Med Genet A* 2003;**118**:180–183.

Sharpe RM. Pathways of endocrine disruption during male sexual differentiation and masculinization. *Best Pract Res Clin Endocrinol Metab* 2006;**20**:91–110.

Shaw GM, O'Malley CD, Wasserman CR, Tolarova MM, Lammer EJ. Maternal periconceptional use of multivitamins and reduced risk for conotruncal heart defects and limb deficiencies among offspring. *Am J Med Genet* 1995;**59**:536–545.

Sheehan DM, Young M. Diethylstilbestrol and estradiol binding to serum albumin and pregnancy plasma of rat and human. *Endocrinology* 1979; **104**:1442–1446.

Shepard TH, Lemire RJ. *Catalog of Teratogenic Agents*, 12th edn. Baltimore: The John Hopkins University Press, 2007.

Shotan A, Widerhorn J, Hurst A, Elkayam U. Risks of angiotensin-converting enzyme inhibition during pregnancy: experimental and clinical evidence, potential mechanisms, and recommendations for use. *Am J Med* 1994;**96**:451–456.

Shuey DL, Sadler TW, Lauder JM. Serotonin as a regulator of craniofacial morphogenesis: site specific malformations following exposure to serotonin uptake inhibitors. *Teratology* 1992;**46**:367–378.

Shuey DL, Sadler TW, Tamir H, Lauder JM. Serotonin and morphogenesis. Transient expression of serotonin uptake and binding protein during craniofacial morphogenesis in the mouse. *Anat Embryol* 1993;**187**:75–85.

Slikker W Jr, Hill DE, Young JF. Comparison of the transplacental pharmacokinetics of 17β- estradiol and diethylstilbestrol in the subhuman primate. *J Pharmacol Exp Ther* 1982;**221**:173–182.

Sly WS, Hu PY. Human carbonic anhydrases and carbonic anhydrase deficiencies. *Annu Rev Biochem* 1995;**64**:375–401.

Smets K, Zecic A, Willems J. Ergotamine as a possible cause of Möbius sequence: additional clinical observation. *J Child Neurol* 2004;**19**:398.

Spranger J, Benirschke K, Hall JG, Lenz W, Lowry RB, Opitz JM, Pinsky L, Schwarzacher HG, Smith DW. Errors of morphogenesis: concepts and terms. Recommendations of an international working group. *J Pediatr* 1982;**100**:160–165.

Stanfield KM, Bell RR, Lisowski AR, English ML, Saldeen SS, Khan KNM. Expression of cyclooxygenase-2 in embryonic and fetal tissues during organogenesis and late pregnancy. *Birth Defects Res A Clin Mol Teratol* 2003;**67**:54–58.

Steegers-Theunissen RP, Boers GH, Blom HJ, Nijhuis JG, Thomas CMG, Borm GF, Eskes TK. Neural tube defects and elevated homocysteine levels in amniotic fluid. *Am J Obstet Gynecol* 1995;**172**:1436–1441.

Stoller JZ, Epstein JA. Cardiac neural crest. *Semin Cell Dev Biol* 2005; **16**:704–715.

Storgaard L, Bonde JP, Olsen J. Male reproductive disorders in humans and prenatal indicators of estrogen exposure. A review of published epidemiological studies. *Reprod Toxicol* 2006;**21**:4–15.

Strachan LR, Condic ML. Neural crest motility on fibronectin is regulated by integrin activation. *Exp Cell Res* 2008;**314**:441–452.

Streck RD, Kumpf SW, Ozolinš TRS, Stedman DB. Rat embryos express transcripts for cyclooxygenase-1 and carbonic anhydrase-4, but not for cyclooxygenase-2, during organogenesis. *Birth Defects Res B Dev Reprod Toxicol* 2003;**68**:57–69.

Swan SH, Main KM, Liu F, Stewart SL, Kruse RL, Calafat AM, Mao CS, Redmon JB, Ternand CL, Sullivan S *et al.* Decrease in anogenital distance among male infants with prenatal phthalate exposure. *Environ Health Perspect* 2005;**113**:1056–1061.

TERIS: Teratogen Information System. Available at: http://depts.washington.edu/terisweb/teris. Retrieved April, 29 2009.

Thiersch JB. Therapeutic abortions with a folic acid antagonist, 4-aminopteroylglutamic acid (4-amino P.G.A.) administered by the oral route. *Am J Obstet Gynecol* 1952;**63**:1298–1304.

Tillakaratne NJK, Erlander MG, Collard MW, Greif KF, Tobin AJ. Glutamate decarboxylases in nonneural cells of rat testis and oviduct: differential expression of GAD_{65} and GAD_{67}. *J Neurochem* 1992;**58**:618–627.

Trocino RA, Akazawa S, Ishibashi M, Matsumoto K, Matsuo H, Yamamoto H, Goto S, Urata Y, Kondo T, Nagataki S. Significance of glutathione depletion and oxidative stress in early embryogenesis in glucose-induced rat embryo culture. *Diabetes* 1995;**44**:992–998.

Tunnicliff G. Molecular basis of buspirone's anxiolytic action. *Pharmacol Toxicol* 1991;**69**:149–156.

U.S. Food and Drug Administration. *Code of Federal Regulations, Title 21*, **Vol. 4**. Washington, DC: U.S. Government Printing Office, 2003, 21–32.

van Aerts LAGJM, Klaasboer HH, Postma NS, Pertijs JCLM, Copius Peereboom JHJ, Eskes TKAB, Noordhoek J. Stereospecific *in vitro* embryotoxicity of L-homocysteine in pre- and post-implantation rodent embryos. *Toxicol in Vitro* 1993;**7**:743–749.

Van Allen MI. Structural anomalies resulting from vascular disruption. *Pediatr Clin North Am* 1992;**39**:255–277.

van der Linden IJM, den Heijer M, Afman LA, Gellekink H, Vermeulen SHHM, Kluijtmans LAJ, Blom HJ. The methionine synthase reductase 66A>G polymorphism is a maternal risk factor for spina bifida. *J Mol Med* 2006;**84**:1047–1054.

van der Put NMJ, van Straaten HWM, Trijbels FJM, Blom HJ. Folate, homocysteine and neural tube defects: an overview. *Exp Biol Med* 2001;**226**:243–270.

van Rooij IALM, Vermeij-Keers C, Kluijtmans LAJ, Ocké MC, Zielhuis GA, Goorhuis-Brouwer SM, van der Biezen JJ, Kuijpers-Jagtman AM, Steegers-Theunissen RPM. Does the interaction between maternal folate intake and the methylenetetrahydrofolate reductase polymorphisms affect the risk of cleft lip with or without cleft palate? *Am J Epidemiol* 2003;**157**:583–591.

van Rooij IALM, Ocké MC, Straatman H, Zielhuis GA, Merkus HMWM, Steegers-Theunissen RPM. Periconceptional folate intake by supplement and food reduces the risk of nonsyndromic cleft lip with or without cleft palate. *Prev Med* 2004;**39**:689–694.

Vanaerts LAGJM, Blom HJ, Deabreu RA, Trijbels FJM, Eskes TKAB, Copius Peereboom-Stegeman JHJ, Noordhoek J. Prevention of neural tube defects by and toxicity of L-homocysteine in cultured postimplantation rat embryos. *Teratology* 1994;**50**:348–360.

Vane JR, Bakhle YS, Botting RM. Cyclooxygenases 1 and 2. *Annu Rev Pharmacol Toxicol* 1998;**38**:97–120.

Vargas FR, Schuler-Faccini L, Brunoni D, Kim C, Meloni VFA, Sugayama SMM, Albano L, Llerena JC Jr, Almeida JCC, Duarte A *et al.* Prenatal exposure to misoprostol and vascular disruption defects: a case–control study. *Am J Med Genet* 2000;**95**:302–306.

Varju P, Katarova Z, Madarász E, Szabó G. GABA signalling during development: new data and old questions. *Cell Tissue Res* 2001;**305**:239–246.

Waldo K, Miyagawa-Tomita S, Kumiski D, Kirby ML. Cardiac neural crest cells provide new insight into septation of the cardiac outflow tract: aortic sac to ventricular septal closure. *Dev Biol* 1998;**196**:129–144.

Waxman JS, Yelon D. Increased Hox activity mimics the teratogenic effects of excess retinoic acid signaling. *Dev Dyn* 2009;**238**:1207–1213.

Wellfelt K, Sköld AC, Wallin A, Danielsson BR. Teratogenicity of the class III antiarrhythmic drug almokalant. Role of hypoxia and reactive oxygen species. *Reprod Toxicol* 1999;**13**:93–101.

Wells PG, Winn LM. Biochemical toxicology of chemical teratogenesis. *Crit Rev Biochem Mol Biol* 1996;**31**:1–40.

Wells PG, Kim PM, Laposa RR, Nicol CJ, Parman T, Winn LM. Oxidative damage in chemical teratogenesis. *Mutat Res* 1997;**396**:65–78.

Wells PG, Bhuller Y, Chen CS, Jeng W, Kasapinovic S, Kennedy JC, Kim PM, Laposa RR, McCallum GP, Nicol CJ *et al.* Molecular and biochemical mechanisms in teratogenesis involving reactive oxygen species. *Toxicol Appl Pharmacol* 2005;**207**:S354–S366.

Werler MM, Hayes C, Louik C, Shapiro S, Mitchell AA. Multivitamin supplementation and risk of birth defects. *Am J Epidemiol* 1999;**150**:675–682.

Werler MM, Sheehan JE, Mitchell AA. Maternal medication use and risks of gastroschisis and small intestinal atresia. *Am J Epidemiol* 2002;**155**:26–31.

Werler MM, Sheehan JE, Hayes C, Mitchell AA, Mulliken JB. Vasoactive exposures, vascular events, and hemifacial microsomia. *Birth Defects Res A Clin Mol Teratol* 2004;**70**:389–395.

Wilcox AJ, Lie RT, Solvoll K, Taylor J, McConnaughey DR, Åbyholm F, Vindenes H, Vollset SE, Drevon CA. Folic acid supplements and risk of facial clefts: national population based case–control study. *Br Med J* 2007;**334**:464.

Wilson JG, Roth CB, Warkany J. An analysis of the syndrome of malformations induced by maternal vitamin A deficiency. Effects of restoration of vitamin A at various times during gestation. *Am J Anat* 1953;**92**:189–217.

Winn LM, Wells PG. Free radical-mediated mechanisms of anti-convulsant teratogenicity. *Eur J Neurol* 1995;**2**:5–29.

Winn LM, Wells PG. Evidence for embryonic prostaglandin H synthase-catalyzed bioactivation and reactive oxygen species-mediated oxidation of cellular macromolecules in phenytoin and benzo[*a*]pyrene teratogenesis. *Free Radic Biol Med* 1997;**22**:607–621.

Winn LM, Wells PG. Maternal administration of superoxide dismutase and catalase in phenytoin teratogenicity. *Free Radic Biol Med* 1999;**26**:266–274.

Wong BY, Coulter DA, Choi DW, Prince DA. Dextrorphan and dextromethorphan, common antitussives, are antiepileptic and antagonize *N*-methyl-D-aspartate in brain slices. *Neurosci Lett* 1988;**85**:261–266.

Yan J, Hales BF. Depletion of glutathione induces 4-hydroxynonenal protein adducts and hydroxyurea teratogenicity in the organogenesis stage mouse embryo. *J Pharmacol Exp Ther* 2006;**319**:613–621.

Yanagisawa H, Yanagisawa M, Kapur RP, Richardson JA, Williams SC, Clouthier DE, de Wit D, Emoto N, Hammer RE. Dual genetic pathways of endothelin-mediated intercellular signaling revealed by targeted disruption of endothelin converting enzyme-1 gene. *Development* 1998;**125**:825–836.

Yavarone MS, Shuey DL, Sadler TW, Lauder JM. Serotonin uptake in the ectoplacental cone and placenta of the mouse. *Placenta* 1993a; **14**:149–161.

Yavarone MS, Shuey DL, Tamir H, Sadler TW, Lauder JM. Serotonin and cardiac morphogenesis in the mouse embryo. *Teratology* 1993b; **47**:573–584.

Yoshida M, Kijima M, Akita M, Beppu T. Potent and specific inhibition of mammalian histone deacetylase both *in vivo* and *in vitro* by trichostatin A. *J Biol Chem* 1990;**265**:17174–17179.

Yu WK, Wells PG. Evidence for lipoxygenase-catalyzed bioactivation of phenytoin to a teratogenic reactive intermediate: *in vitro* studies using linoleic acid-dependent soybean lipoxygenase, and *in vivo* studies using pregnant CD-1 mice. *Toxicol Appl Pharmacol* 1995; **131**:1–12.

Zaken V, Kohen R, Ornoy A. The development of antioxidant defense mechanism in young rat embryos *in vivo* and *in vitro*. *Early Pregnancy* 2000;**4**:110–123.

Zhang HY, Luo GA, Liang QL, Wang Y, Yang HH, Wang YM, Zheng XY, Song XM, Chen G, Zhang T *et al.* Neural tube defects and disturbed maternal folate- and homocysteine-mediated one-carbon metabolism. *Exp Neurol* 2008;**212**:515–521.

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