DIETHYLSTILBESTROL

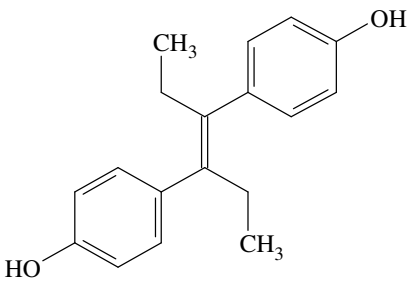
Diethylstilbestrol was considered by previous Working Groups in November 1978 (volume 21, IARC, 1979a), and in March 1987 (Supplement 7, IARC, 1987a). Since that time, new data have become available, and these have been incorporated into the monograph, and taken into consideration in the present evaluation

1. Exposure Data

1.1 Identification and description of the agent

Chem. Abstr. Serv. Reg. No.: 56–53–1
Chem. Abstr. Name: Phenol, 4,4'-[(1*E*)-1,2-diethyl-1,2-ethenediyl]bis-
IUPAC Systematic Name: 4-[(*E*)-4-(4-Hydroxyphenyl)hex-en-3-yl]phenol
Synonyms: (*E*)-3,4-Bis(4-hydroxyphenyl)-3-hexene; (*E*)-4,4'-(1,2-diethyl-1,2-ethenediyl)bisphenol; (*E*)-diethylstilbestrol; α,α′-diethyl-4,4'-stilbenediol; α,α′-diethylstilbenediol; 4,4'-dihydroxy-α,β-diethylstilbene; 4,4'-dihydroxydiethylstilbene; phenol, 4,4'-(1,2-diethyl-1,2-ethenediyl)bis-, (*E*)-; 4,4'-stilbenediol, α,α′-diethyl-, *trans*-;
Description: white, odourless, crystalline powder (McEvoy, 2007)

a) Structural and molecular formulae, and relative molecular mass



$C_{18}H_{20}O_2$
Relative molecular mass: 268.35

1.2 Use of the agent

Information for Section 1.2 is taken from IARC (1979a), McEvoy (2007), Royal Pharmaceutical Society of Great Britain (2007), and Sweetman (2008).

1.2.1 Indications

Diethylstilbestrol is a synthetic nonsteroidal estrogen that was historically widely used to prevent potential miscarriages by stimulating the synthesis of estrogen and progesterone in the placenta (in the United States of America, especially

from the 1940s to the 1970s) (Rogers & Kavlock, 2008). It was also used for the treatment of symptoms arising during menopause and following ovariectomy, and for senile (atrophic) vaginitis and vulvar dystrophy. Diethylstilbestrol was employed as a postcoital emergency contraceptive ('morning-after pill'). It has been used for the prevention of postpartum breast engorgement, for dysfunctional menstrual cycles, and for the treatment of female hypogonadism.

Diethylstilbestrol is now rarely used to treat prostate cancer because of its side-effects. It is occasionally used in postmenopausal women with breast cancer.

Diethylstilbestrol was also used as a livestock growth stimulant.

1.2.2 Dosages

Historically, diethylstilbestrol was used for the treatment of symptoms arising during the menopause (climacteric) and following ovariectomy in an oral daily dose of 0.1–0.5 mg in a cyclic regimen. For senile vaginitis and vulvar dystrophy, it was given in an oral daily dose of 1 mg, or, for vulvar dystrophies and atrophic vaginitis, in suppository form in a daily dose of up to 1 mg. As a postcoital emergency contraceptive ('morning-after pill'), it was given as an oral dose of 25 mg twice a day for 5 days starting within 72 hours of insemination. An oral dose of 5 mg 1–3 times per day for a total of 30 mg was typically given in combination with methyltestosterone for the prevention of postpartum breast engorgement. For dysfunctional uterine bleeding, diethylstilbestrol was given in an oral dose of 5 mg 3–5 times per day until bleeding stopped. It was also used for the treatment of female hypogonadism, in an oral dose of 1 mg per day (IARC, 1979a; McEvoy, 2007).

The typical dosage of diethylstilbestrol is 10–20 mg daily to treat breast cancer in postmenopausal women, and 1–3 mg daily to treat prostate cancer. Diethylstilbestrol has also been given to treat prostate cancer in the form of its diphosphate salts (Fosfestrol).

When used as pessaries in the short term management of menopausal atrophic vaginitis, the daily dose was 1 mg (Royal Pharmaceutical Society of Great Britain, 2007; Sweetman, 2008).

Diethylstilbestrol is available as 1 mg and 5 mg tablets for oral administration in several countries (Royal Pharmaceutical Society of Great Britain, 2007).

Diethylstilbestrol is no longer commercially available in the USA (McEvoy, 2007).

1.2.3 Trends in use

Most reports about diethylstilbestrol use are from the USA. The number of women exposed prenatally to diethylstilbestrol worldwide is unknown. An estimated 5 to 10 million Americans received diethylstilbestrol during pregnancy or were exposed to the drug *in utero* from the 1940s to the 1970s (Giusti *et al.*, 1995).

A review of 51000 pregnancy records at 12 hospitals in the USA during 1959–65 showed geographic and temporal variation in the percentage of pregnant women exposed: 1.5% of pregnancies at the Boston Lying-In Hospital, and 0.8% at the Children's Hospital in Buffalo were exposed to diethylstilbestrol; at the remaining ten hospitals, 0.06% of pregnant women were exposed (Heinonen, 1973). At the Mayo Clinic during 1943–59, 2–19% (mean, 7%) of pregnancies per year were exposed (Lanier *et al.*, 1973).

The peak years of diethylstilbestrol use in the USA varied from 1946–50 at the Mayo Clinic, Minnesota, 1952–53 at the Massachusetts General Hospital in Boston, and 1964 at the Gundersen Hospital in Wisconsin (Nash *et al.*, 1983). Over 40% of the women in the DESAD cohort were exposed during the early 1950s (1950–55) (Herbst & Anderson, 1990). Among cases of clear cell adenocarcinoma of the cervix and vagina recorded in the Central Netherlands Registry, born during 1947–73, the median year of birth

was 1960 (Hanselaar *et al.*, 1997). In the Registry for Research on Hormonal Transplacental Carcinogenesis, which registers cases of clear cell adenocarcinoma of the vagina and cervix in the USA, Australia, Canada, Mexico and Europe, most of the exposed women from the USA were born during 1948–65 (Herbst, 1981; Melnick *et al.*, 1987).

Diethylstilbestrol doses varied by hospital. Based on the record review at 12 hospitals in the USA, the highest doses were administered at the Boston Lying-in, where 65% of treated pregnant women received total doses higher than 10 g, up to 46.6 g, for a duration of up to 9 months. At all the other hospitals, most women (74%) received < 0.1 g (Heinonen, 1973). Data available from the US National Cooperative Diethylstilbestrol Adenosis (DESAD) project indicate that median doses were 3650 mg (range 6–62100 mg) for women identified through the record review, whereas the median dose exceeded 4000 mg for women who entered the cohort through referral (self or physician), more of whom were affected by diethylstilbestrol-related tissue changes (O'Brien *et al.*, 1979). Diethylstilbestrol doses may have varied over time, but this has not been reported.

The use of diethylstilbestrol and other estrogens during pregnancy is now proscribed in many countries (Anon, 2008), and diethylstilbestrol use is no longer widespread for other indications.

Until the 1970s, it was common practice to stimulate the fattening of beef cattle and chickens by mixing small amounts of diethylstilbestrol into the animal feed or by implanting pellets of diethylstilbestrol under the skin of the ears of the animals. In the early 1970s, concern over trace amounts of the hormone in meat led to bans on the use of diethylstilbestrol as a livestock growth stimulant (Anon, 2008).

2. Cancer in Humans

The previous IARC monograph (IARC, 1987a) states that there is sufficient evidence of a causal association between clear cell adenocarcinoma of the vagina/cervix and prenatal exposure to diethylstilbestrol. That monograph also cited clear evidence of an increased risk of testicular cancer in prenatally diethylstilbestrol-exposed male offspring, an association that is now uncertain due to the publication of recent studies. The association between diethylstilbestrol administered during pregnancy and breast cancer was considered established, but the latent period remained uncertain. Evidence was mixed for an association between diethylstilbestrol exposure during pregnancy and cancers of the uterus, cervix, and ovary. Finally, the IARC monograph states that there is sufficient evidence of a causal relationship between uterine cancer and use of diethylstilbestrol as hormonal therapy for menopausal symptoms.

The studies cited in this review represent key historical reports relevant to the association between diethylstilbestrol and human cancer. Only studies of key cancer end-points published since the most recent IARC monograph in 1987 are shown in the tables.

2.1 Women exposed to diethylstilbestrol during pregnancy

2.1.1 Breast cancer incidence

Historically, nearly all of the studies assessing diethylstilbestrol in relation to invasive breast cancer incidence or mortality involve the retrospective and/or prospective follow-up of women with verified exposure to diethylstilbestrol during pregnancy. The results of some early studies suggested modestly increased risk, with relative risks (RR) ranging from 1.37 to 1.47 (Clark & Portier,

1979; Greenberg et al., 1984; Hadjimichael et al., 1984). However, a standardized incidence ratio (SIR) of 2.21 was reported from the Dieckmann clinical trial cohort (Hubby et al., 1981), despite null results from an earlier analysis of the same cohort (Bibbo et al., 1978). Historically, null results were also reported from a small US cohort (eight cases) (Brian et al., 1980), and two small cohorts arising from separate clinical trials in London, the United Kingdom (four and 13 cases, respectively) (Beral & Colwell, 1981; Vessey et al., 1983).

Two reports published since the previous IARC monograph are consistent with a modest association between diethylstilbestrol exposure during pregnancy and breast cancer incidence (see Table 2.1 available et http://monographs.iarc.fr/ENG/Monographs/vol100A/100A-11-Table2.1.pdf). The first of these (Colton et al., 1993) was based on further follow-up of the Women's Health Study (WHS) (Greenberg et al., 1984). The WHS cohort was originally assembled at three US medical centres (Mary Hitchcock Memorial Hospital in Hanover; Boston Lying-in Hospital in Boston; Mayo Clinic in Rochester) and a private practice in Portland (Greenberg et al., 1984). At all participating WHS centres, diethylstilbestrol exposure (or lack of exposure) during pregnancy was based on a review of obstetrics records during 1940–60. Although exact diethylstilbestrol doses administered to women in the WHS are largely unknown, they are believed to have been relatively low. In the 1989 WHS follow-up, health outcomes, including breast cancer diagnosis and mortality, were retrospectively and prospectively ascertained in 2864 exposed and 2760 unexposed women. The data produced a relative risk of 1.35 for breast cancer risk based on 185 exposed and 140 unexposed cases (Colton et al., 1993), whereas the earlier study reported a relative risk of 1.47 (Greenberg et al., 1984).

The second report was based on the US National Cancer Institute (NCI) Combined Cohort Study, which in 1994 combined and extended follow-up of the WHS cohort (by 5 years), and the Dieckmann clinical trial cohort (by 14 years). The Dieckmann clinical trial was conducted in 1951–52 (Dieckmann et al., 1953) to assess the efficacy of diethylstilbestrol for preventing adverse pregnancy outcomes. Administered diethylstilbestrol doses were high, with a cumulative dose of 11–12 g (Bibbo et al., 1978). The combined WHS and Dieckmann cohorts produced a modestly elevated relative risk of 1.25 for breast cancer (Titus-Ernstoff et al., 2001).

Based on data from the Dieckmann clinical trial cohort (Hubby et al., 1981) and the NCI Combined Cohort Study (Titus-Ernstoff et al., 2001), the influence of diethylstilbestrol on breast cancer risk did not differ according to family history of breast cancer, reproductive history, prior breast diseases, or oral contraceptive use. Although the first follow-up of the Dieckmann clinical trial cohort suggested breast cancer occurred sooner after trial participation in the diethylstilbestrol-exposed women (Bibbo et al., 1978), this was not seen in the subsequent follow-up (Hubby et al., 1981), in the WHS cohort (Greenberg et al., 1984; Colton et al., 1993), in the NCI Combined Cohort Study (Titus-Ernstoff et al., 2001), or the Connecticut study (Hadjimichael et al., 1984). In both the NCI Combined Cohort Study (Titus-Ernstoff et al., 2001) and the Connecticut study (Hadjimichael et al., 1984), the elevated risk associated with diethylstilbestrol was not apparent 40 or more years after exposure.

Data from the WHS (Greenberg et al., 1984) and the Dieckmann clinical trial cohort (Bibbo et al., 1978; Hubby et al., 1981) did not show systematic differences in breast tumour size, histology or stage at diagnosis for the diethylstilbestrol-exposed and -unexposed women. No differences between exposed and unexposed women with regard to breast self-examination or mammography screening were noted in follow-up data from the WHS (Colton et al., 1993) [The Working Group noted it seemed unlikely

the increased risk in diethylstilbestrol-exposed women was due to an increased surveillance of exposed women or to confounding by lifestyle factors.]

Historically, a few studies have suggested an association between exposure to diethylstilbestrol during pregnancy and an increased risk of breast cancer mortality; these include an analysis based on the first follow-up report of women in the Dieckmann clinical trial (RR, 2.89; 95% CI: 0.99– 8.47) (Clark & Portier, 1979), and a study in Connecticut (RR, 1.89; 95% CI: 0.47–7.56) (Hadjimichael et al., 1984). More recent studies are consistent with a modest association, including an analysis of fatal breast cancer in a large American Cancer Society (ACS) cohort of gravid women (RR, 1.34; 95% CI: 1.06–1.69) (Calle et al., 1996), the second follow-up of women in the WHS (RR, 1.27; 95% CI: 0.84–1.91) (Colton et al., 1993), and the NCI Combined Cohort Study, which for this analysis combined and extended the follow-up of the WHS women by 8 years and the Dieckmann women by 17 years (hazard ratio [HR] 1.38; 95% CI: 1.03–1.85) (Titus-Ernstoff et al., 2006a). Similar to the NCI study of breast cancer incidence (Titus-Ernstoff et al., 2001), the ACS study showed that risk of breast cancer mortality did not differ by family history of breast cancer, reproductive history, or hormone use; also, the elevated risk was no longer evident 40 or more years after exposure (Calle et al., 1996).

In summary, evidence from large, recent cohort studies suggests a modest association between diethylstilbestrol exposure during pregnancy and increased breast cancer incidence and mortality. Notably, these associations were apparent in women participating in the Dieckmann clinical trial cohort, minimizing the possibility of distortion due to confounding by the clinical indication for diethylstilbestrol use. The increased risk of breast cancer mortality also argues against an artefactual association stemming from the heightened surveillance of diethylstilbestrol-exposed women.

Diethylstilbestrol was also prescribed for the treatment of menopausal symptoms, but the use of diethylstilbestrol in menopause has not been assessed systematically in relation to breast cancer risk, and the association is unclear.

2.1.2 Other cancer sites

An early study suggested a relationship between the use of diethylstilbestrol to treat gonadal dysgenesis and risk of endometrial cancer in young women (Cutler et al., 1972). An increased risk of endometrial cancer was also reported in association with the use of diethylstilbestrol to treat symptoms of menopause (Antunes et al. 1979).

Two follow-up studies indicated (Hoover et al., 1977) or suggested (Hadjimichael et al., 1984) an increased risk of ovarian cancer among women exposed to diethylstilbestrol during pregnancy, but the number of exposed cases was small. Similarly, early attempts to assess the risk of cervical and other cancers were limited by small case numbers (Hadjimichael et al., 1984). The large and more recent NCI Combined Cohort study did not show an association between diethylstilbestrol exposure during pregnancy and the incidence of cancer of the endometrium, ovary, or cervix (Titus-Ernstoff et al., 2001).

Although relative risks were elevated for brain and lymphatic cancers in the Connecticut study (Hadjimichael et al., 1984) and for stomach cancer in the NCI Combined Cohort Study (Titus-Ernstoff et al., 2001), confidence intervals were wide. A recent report from the large ACS study showed no association between diethylstilbestrol taken during pregnancy and pancreatic cancer mortality (1959 deaths in 387981 women) (Teras et al., 2005). The NCI Combined Cohort study did not find associations between diethylstilbestrol exposure during pregnancy and death due to cancers other than breast cancer (Titus-Ernstoff et al., 2006a).

2.2 Women exposed *in utero*

2.2.1 Clear cell adenocarcinoma of the vagina and cervix

Substantial evidence indicates that women exposed *in utero* to diethylstilbestrol have a markedly increased risk of clear cell adenocarcinoma (CCA) of the vagina and cervix. The earliest report, published in 1970, described seven cases of adenocarcinoma (six CCA) in women of ages 15–22 who had been exposed prenatally to diethylstilbestrol (Herbst & Scully, 1970). The following year, a case–control study based on these seven cases plus an additional case (eight cases) and 32 matched controls showed a strong statistical association between prenatal diethylstilbestrol exposure and risk of vaginal CCA based on seven exposed cases and zero exposed controls ($P < 0.00001$) (Herbst et al., 1971). A second case–control study published the same year, involving five cases identified through the New York State Cancer Registry and eight matched controls, also supported an association between prenatal exposure to synthetic estrogens and vaginal CCA based on five exposed cases and zero exposed controls (Greenwald et al., 1971). The strength of this evidence was based primarily on the rarity of CCA, particularly in young women, and on the high proportion of cases that were exposed to a medication that was used relatively infrequently. Based on these reports, the US Food and Drug Administration issued a bulletin against prescribing diethylstilbestrol during pregnancy in late 1971 (Anon, 1972).

Additional evidence published in 1972 established a link between prenatal diethylstilbestrol exposure and CCA. That study identified seven cases of CCA occurring in girls aged 7–19 years; of the four mothers who were successfully contacted, three reported diethylstilbestrol use during the first trimester of pregnancy and one reported taking a hormone of unknown type for vaginal bleeding (Noller et al., 1972). A study of the California Tumor Registry during 1950–69 showed an increase of vaginal tumours in girls aged 10–19 years (Linden & Henderson, 1972). Subsequent case series, two of which were based in California, supported the link between prenatal diethylstilbestrol exposure and CCA at both sites (Henderson et al., 1973; Hill, 1973).

The only follow-up study of prenatal diethylstilbestrol exposure in relation to risk of CCA is the NCI Combined Cohort Study, which combined pre-existing US cohorts with verified diethylstilbestrol exposure (or lack of exposure) including:

daughters of women who participated in the Dieckmann clinical trial (Dieckmann et al., 1953),

daughters of women enrolled in the WHS (Greenberg et al., 1984),

daughters of women treated with diethylstilbestrol at a Boston infertility clinic and their unexposed sisters (the Horne cohort), and

more than 5000 women (including more than 4000 exposed) who were initially identified through medical records or referral (self or physician), and enrolled during the 1970s in the multicentre US National Cooperative DESAD project (Labarthe et al., 1978).

Follow-up of the NCI Combined Cohort through 1994 ascertained three diethylstilbestrol-exposed cases of vaginal CCA, producing an SIR of 40.7 (95% CI: 13.1–136.2). Continued follow-up through 2001 ascertained an additional exposed case of cervical CCA, producing an SIR of 39 (95% CI: 15–104) (see Table 2.2 available at http://monographs.iarc.fr/ENG/Monographs/vol100A/100A-11-Table2.2.pdf), and indicating a cumulative risk of 1.6 per 1000 of CCA of the vagina/cervix from birth through age 39 (Troisi et al., 2007).

An early study comparing internationally ascertained diethylstilbestrol-exposed CCA cases, recorded in the Registry for Research on Transplacental Carcinogenesis at the University of Chicago, to diethylstilbestrol-exposed

non-cases in the DESAD study suggested that CCA risk is influenced by early gestational exposure, but not by dose. Evidence was unclear for an influence of prior miscarriage (Herbst et al., 1986). Another University of Chicago registry-based study published since the previous IARC monograph found that maternal vaginal bleeding during pregnancy was not associated with case status, reducing the likelihood that pregnancy complications confounded the association between diethylstilbestrol and CCA (Sharp & Cole, 1990). The same study also found that CCA occurring in diethylstilbestrol-exposed women was associated with earlier gestational exposure and with greater body weight and greater height at ages 14–15 years (Sharp & Cole, 1991) [The Working Group noted that, possibly, greater body weight and height in the early teenage years was a proxy for early puberty, which may have increased the time at risk.] A recent study comparing diethylstilbestrol-exposed CCA cases to diethylstilbestrol-controls did not identify postnatal factors that influenced risk of this cancer (Palmer et al., 2000).

Vaginal adenosis is an established, although non-obligatory, precursor of CCA that affects between 34–88% of diethylstilbestrol-exposed women (Antonioli & Burke, 1975; Bibbo et al., 1975; Herbst et al., 1975; Kaufman & Adam, 1978; O'Brien et al., 1979) and fewer than 4% of unexposed women (Bibbo et al., 1975; Herbst et al., 1975). The lower prevalence (34–35%) was found in diethylstilbestrol-exposed women who were identified through a medical record review (Herbst et al., 1975; Robboy et al., 1979); also, in these studies, tissues were biopsied only when changes were seen upon clinical examination or colposcopy. The higher prevalence (88%) was reported in women many of whom had been referred for study because of other diethylstilbestrol-related vaginal anomalies (Antonioli & Burke, 1975). Several studies suggested the likelihood of vaginal epithelial changes, including adenosis, is greater in women who received higher diethylstilbestrol doses (O'Brien et al., 1979), women of young ages (aged 13–26 years in Mattingly & Stafl; 1976), and women who were exposed early in gestation (defined variously as before Week 16, before 19 or 20 weeks, or during the first trimester) (Herbst et al., 1975; Mattingly & Stafl, 1976; Kaufman & Adam, 1978; O'Brien et al., 1979). A decreasing prevalence with age has been seen in case series (Kaufman et al., 1982), in the DESAD study (Robboy et al., 1981) and in prospective follow-up studies of diethylstilbestrol-exposed women, suggesting possible regression (Burke et al., 1981; Noller et al., 1983). Although most women affected by adenosis do not develop CCA, adenosis is present in up to 100% of vaginal CCA (Herbst et al., 1972; Herbst et al., 1974; Robboy et al., 1984a).

2.2.2 Squamous neoplasia of the cervix

Around the time of puberty, the outer cervical epithelium undergoes a transition from the original columnar epithelium to squamous epithelium. The area affected by this change (squamous metaplasia), known as the cervical transformation zone (squamo-columnar junction), is at increased risk of malignancy. Early clinical series suggested the extended transformation zone associated with prenatal diethylstilbestrol exposure might increase susceptibility for squamous neoplasia/dysplasia in these women (Stafl & Mattingly, 1974; Fetherston, 1975; Fowler et al., 1981). A study comparing diethylstilbestrol-exposed and -unexposed women showed a higher percent of dysplastic squamous cells in the exposed (11%) than in the unexposed (7%) based on cytology; the prevalence was greater (27%) in exposed women with pathologically confirmed adenosis (Herbst et al., 1975). In a subsequent study of 280 women exposed to diethylstilbestrol in the first trimester, 82% were affected by adenosis and nearly all (96%) of these had abnormal colposcopic findings (Mattingly & Stafl, 1976).

The baseline examination of the DESAD study women who were identified through medical record review did not find elevated rates of squamous dysplasia in the diethylstilbestrol-exposed group (Robboy et al., 1981), but the 7-year follow-up of 1488 (744 exposed) women noted higher rates of cervical squamous cell dysplasia and carcinoma *in situ* in the diethylstilbestrol-exposed compared to the unexposed women (15.7 versus 7.9 cases per 1000 person–years) based on cytology or biopsy (Robboy et al., 1984b). The difference between exposed and unexposed was more apparent when the analyses were confined to cases identified through biopsy (as opposed to cytology) (5.0 versus 0.4 cases per 1000 person–years) (Robboy et al., 1984b). [The Working Group noted that studies relying on selective biopsy may exaggerate the association between prenatal diethylstilbestrol exposure and risk of cervical neoplasia.] A recent analysis of the NCI Combined Cohort Study showed a doubling of the risk of high-grade intraepithelial neoplasia (squamous cell dysplasia) in the women exposed prenatally to diethylstilbestrol compared to the unexposed; the risk appeared to be higher for those with intrauterine exposure within 7 weeks of the last menstrual period (RR, 2.8; 95% CI: 1.4–5.5) (Hatch et al., 2001). There were not enough confirmed cases of invasive cervical cancer for a meaningful analysis.

A study of 5421 questionnaire respondents (representing 41% of 13350 queried) who had been enrolled previously in the Netherlands Diethylstilbestrol Information Centre (NDIC), in which prenatal diethylstilbestrol exposure was validated using medical records, found evidence of a 5-fold risk (prevalence ratio [PrR]: 5.4; 95% CI: 2.8–9.5) of confirmed non-clear-cell-adenocarcinoma cervical cancer in comparison to the number of cases expected based on age and calendar year rates derived from a cancer registry (Verloop et al., 2000) [The Working Group noted that because a low proportion of women returned their questionnaires, participation bias may have inflated the PrR.]

2.2.3 Cancer of the breast

A study in the Netherlands based on 5421 questionnaires returned to the NDIC found a modestly elevated risk of breast cancer for diethylstilbestrol-exposed women, but the confidence intervals were wide (PrR, 1.5; 95% CI: 0.7–2.9) (Verloop et al., 2000). Findings based on the 1994 and 2001 follow-up of the NCI Combined Cohort Study did not show an overall increase of breast cancer rates in prenatally exposed women (Hatch et al., 1998; Troisi et al., 2007) (see Table 2.3 available at http://monographs.iarc.fr/ENG/Monographs/vol100A/100A-11-Table2.3.pdf). Relative risks from the two reports were 1.18 (95% CI: 0.56–2.49) (Hatch et al., 1998) and 1.35 (95% CI: 0.85–2.10) (Troisi et al., 2007). A more detailed analysis of the 2001 follow-up data gave an incidence rate ratio (IRR) of 2.05 (95% CI: 1.12–3.76) in women aged 40 years or more, and 0.57 (95% CI: 0.24–1.34) in women aged less than 40 years. The data also showed an elevated risk for women aged 50 years or more (IRR, 3.85; 95% CI: 1.06–14.0) (Palmer et al., 2006) [The Working Group noted that women aged 50 years or more contributed 3% of the person–years in these analyses.] While speculative, women approaching the age of 50 years in this cohort would have been exposed during the peak years (1952–3 for the Dieckmann clinical trial and DESAD cohort members), which might have involved higher doses. If the association is real, the increased risk in older women might reflect higher exposure rather than age-related risk. In the same study, risk appeared to be elevated for older women with high (versus low) diethylstilbestrol exposure classified using known dose (38%) or assumed dose based on geographic region. There was no evidence that the risk in women aged 40 years or more was influenced by the timing of gestational exposure, which was known for 75%

of the exposed subjects. Also, there was no indication of effect modification by known breast cancer risk factors. Diethylstilbestrol exposure did not influence the receptor status of the breast tumour or lymph node involvement, but the association was evident in women with larger tumours (≥ 2 cm), arguing against screening bias (Palmer et al., 2006).

2.2.4 Other sites

The study based on the NDIC produced a prevalence ratio of 2.9 (95% CI: 0.8–7.5) based on four cases of ovarian cancer observed in women prenatally exposed to diethylstilbestrol (1.36 cases expected) (Verloop et al., 2000). The NCI Combined Cohort Study, however, showed no evidence of an association between prenatal diethylstilbestrol exposure and ovarian cancer in the 1994 or 2001 follow-up (Hatch et al., 1998; Troisi et al., 2007). The SIR was 0.88 (95% CI: 0.44–1.80) based on eight cases in the exposed at the time of the 2001 follow-up (Troisi et al., 2007).

Based on one case, the NDIC study suggested an association between prenatal diethylstilbestrol exposure and vulvar cancer (PrR, 8.8; 95% CI: 0.2–49.0) but confidence intervals were wide (Verloop et al., 2000).

The NCI Combined Cohort Study found no evidence of an association between prenatal diethylstilbestrol exposure and endometrial cancer (SIR, 1.04; 95% CI: 0.52–2.10) based on eight cases in the exposed (Troisi et al., 2007).

The NCI Combined Cohort Study suggested possible increases of lymphoma, lung and brain/nervous system cancers in prenatally exposed women, but the estimates were imprecise and compatible with chance (Troisi et al., 2007). Sites for which there was no indication of increased risk included the thyroid and colorectum (Troisi et al., 2007).

Based on the present studies of women, there is scant evidence to support an association between prenatal exposure to diethylstilbestrol and tumours other than the established relationship with clear cell adenocarcinoma affecting the cervix and vagina.

2.3 Men exposed to diethylstilbestrol

2.3.1 Men exposed through cancer therapy

Early case reports of breast cancer occurring in prostate cancer patients treated with diethylstilbestrol implied a possible link; however, the extent to which some of these tumours represented metastatic prostate cancer is uncertain (Bülow et al., 1973).

2.3.2 Men exposed in utero

(a) Cancer of the testes

Several studies have examined prenatal diethylstilbestrol exposure in relation to testicular cancer, but findings have been inconsistent. Because the diethylstilbestrol-exposed men now have passed the age of highest risk for testicular cancer, the question of an association is likely to remain unanswered.

Based on the findings from several case–control studies examining this relationship, most of which relied completely (Henderson et al., 1979; Schottenfeld et al., 1980; Depue et al., 1983; Brown et al., 1986) or partly (Moss et al., 1986) on self-reported hormone use, the previous IARC monograph concluded there is sufficient evidence of a relationship between prenatal diethylstilbestrol exposure and testicular cancer. Three of the contributing studies found possible evidence of an association (; Henderson et al., 1979; Schottenfeld et al., 1980; Depue et al., 1983) and two did not (Brown et al., 1986; Moss et al., 1986). Of the three studies that found possible evidence, the association was not of statistical significance in two (Henderson et al., 1979; Schottenfeld et al., 1980). The strongest association arose from a study in California that assessed hormone use during the

first trimester of pregnancy with a relative risk of 8.00 (95% CI: 1.3–4.9); 2/9 case mothers (and none of the control mothers) specified using diethylstilbestrol (Depue et al., 1983). Data from some studies showed (Brown et al., 1986) or suggested (Schottenfeld et al., 1980) an increased risk for the sons of women who had experienced spotting or bleeding during the index pregnancy, a possible marker for diethylstilbestrol use not recalled by the mother. Four of the contributing studies relied partly (Schottenfeld et al., 1980) or entirely (Henderson et al., 1979; Depue et al., 1983; Moss et al., 1986) on neighbourhood controls [The Working Group noted both of these approaches may have resulted in overmatching and attenuation of a possible relationship between prenatal diethylstilbestrol exposure and risk of testicular cancer]. In the setting of diethylstilbestrol, it is also possible the mothers' reporting was inaccurate, in part because of the amount of time that had passed since the pregnancy and in part because women of the diethylstilbestrol era were not always given complete information about their medical care [The Working Group noted that errors of recall or recall bias may have influenced the results of these studies.]

Early cohort studies of men exposed *in utero* to diethylstilbestrol also have been largely inconclusive. No testicular cancer cases were identified in the sons of women exposed to high doses of diethylstilbestrol through participation in the Dieckmann clinical trial (11–12 g) (Gill et al., 1979), or a clinical trial involving diabetic women in the United Kingdom (mean of 17.9 g) (Beral & Colwell, 1980), although both cohorts were small. One case of fatal teratoma was ascertained in the 138 exposed (no cases in the unexposed) sons of women who participated in a separate high dose (mean of 11.5 g) clinical trial at the University College Hospital in London (Vessey et al., 1983).

Two studies have been published since the previous IARC monograph. The first study, a case–control design, matched controls to cases by obstetrician (Gershman & Stolley, 1988) (see Table 2.4 available at http://monographs.iarc.fr/ENG/Monographs/vol100A/100A-11-Table2.4.pdf). The source of diethylstilbestrol exposure status was unclear, but apparently was not based on the medical record. The analysis did not show an association between prenatal diethylstilbestrol exposure and testicular cancer. The NCI Combined Cohort Study assessed 2759 (1365 exposed, 1394 unexposed) sons born to women in the WHS study, the Dieckmann clinical trial, and the Horne cohort, as well as sons identified through the Mayo Clinic with retrospective follow-up for an average of 16.9 years (1978–94) (Strohsnitter et al., 2001) (see Table 2.5 available at http://monographs.iarc.fr/ENG/Monographs/vol100A/100A-11-Table2.5.pdf). For all participants, diethylstilbestrol exposure (or lack of exposure) was verified by the medical or clinical trial record. In this study, the SIR for prenatally exposed men was 2.04 (95% CI: 0.82–4.20) based on seven cases observed in the exposed and 3.4 expected. The relative risk was 3.05 (95% CI: 0.65–22.0) in the internal comparison (two unexposed cases). None of the cases in the NCI Combined Cohort study arose from the Dieckmann clinical trial cohort in which women were consistently given high doses of diethylstilbestrol (cumulative dose of 11–12 g) during the first trimester, although the subcohort was small in size (205 exposed, 187 unexposed). All of the elevated risk was due to an excess of exposed cases arising in the Mayo cohort (five cases in 660 exposed, one case in 592 unexposed). Among those for whom diethylstilbestrol dose was known, the mothers of cases and noncases received 12.5 and 10 mg/day, respectively, doses that are lower than those received by the Dieckmann clinical trial or Horne cohorts (Strohsnitter et al., 2001). The relative risk was unchanged when the analyses were confined to 138 men whose mothers were given diethylstilbestrol during the first trimester of pregnancy but increased to 5.91 (95% CI: 1.05–46.1) after excluding from the analysis men who

were exposed prenatally to both diethylstilbestrol and progestogen.

Cryptorchidism increases the risk for testicular cancer (Sarma et al., 2006). An increased prevalence of cryptorchidism was not seen in the exposed men in either of the two small cohort studies involving the sons of women who received high doses through participation in separate clinical trials in the United Kingdom (a mean of 17.9 g in Beral & Colwell, 1980; mean of 11.5 g in Vessey et al., 1983). However, an increased prevalence of cryptorchidism (17/308 exposed versus 1/307 unexposed; $P < 0.005$) was seen in the sons of women exposed to high doses of diethylstilbestrol through participation in the Dieckmann clinical trial (Gill et al., 1979), suggesting a possible pathway linking diethylstilbestrol and testicular cancer (no cases were noted). In the case–control study that addressed this connection, only 1/22 testicular cancer cases affected by cryptorchidism was also exposed to diethylstilbestrol (Schottenfeld et al., 1980).

(b) Other sites

In the NCI Combined Cohort Study, findings were suggestive for bone and thyroid cancer, but estimates were imprecise.

2.4 Offspring (third generation) of women who were exposed to diethylstilbestrol *in utero*

2.4.1 Third generation women

Follow-up of the prenatally exposed and unexposed second generation women participating in the NCI Combined Cohort in 1994, 1997, and 2001 included inquiries about cancers occurring in their offspring (Titus-Ernstoff et al., 2008) (see Table 2.6 available at http://monographs.iarc.fr/ENG/Monographs/vol100A/100A-11-Table2.6.pdf). Based on the mothers' unconfirmed reports, two cases of ovarian cancer occurred (diagnoses at ages 7 and 20 years) in the 2539 daughters of prenatally exposed women. The SIR in the exposed was 5.3 (95% CI: 1.3–21) based on 0.38 cases expected. No cases were reported in the 1423 unexposed third generation daughters.

In 2001, the NCI Combined Cohort Study initiated a follow-up study of the adult daughters of women who either had or had not been exposed to diethylstilbestrol *in utero* (Titus-Ernstoff et al., 2008). The results of the baseline survey, which enrolled 793 third generation women (463 exposed, 330 unexposed), confirmed two cases of ovarian cancer in exposed women (diagnosis ages of 20 and 22), including one of the cases that had been reported by the mother. No cases of ovarian cancer were observed in the daughters of women who were not exposed to diethylstilbestrol *in utero*. The SIR was 14.68 (95% CI: 3.67–58.71) based on 0.14 expected cases. Because only half of the second generation women had allowed contact with their daughters, participation bias was a possible explanation for this finding. However, the SIR remained elevated (6.6; 95% CI: 1.7–26) when based on all adult daughters of prenatally exposed women, regardless of whether they participated in the third generation study (0.30 cases expected).

Only one study involved clinical examinations of third generation women (Kaufman & Adam, 2002). Most of the mothers had a history of diethylstilbestrol-related changes, but no vaginal or cervical anomalies were noted upon colposcopic examination of 28 third-generation daughters. Although the study was based on small numbers and did not include hysterosalpingography, the absence of anomalies is inconsistent with the high prevalence of diethylstilbestrol-related vaginal epithelial changes affecting prenatally exposed women.

2.4.2 Third generation men

In the NCI Combined Cohort Study and based on the mothers' reports, the SIR provided no evidence of increased cancer risk in men born to women exposed prenatally to diethylstilbestrol.

2.5 Synthesis

A large body of evidence was evaluated for several organ sites, among which the Working Group concluded that diethylstilbestrol is associated with cancer of the breast in women who were exposed while pregnant. Diethylstilbestrol also causes clear cell adenocarcinoma in the vagina and cervix of women who were exposed *in utero*. Finally, a positive association has been observed between exposure to diethylstilbestrol and cancer of the endometrium, and between in-utero exposure to diethylstilbestrol and squamous-cell carcinoma of the cervix, and cancer of the testis.

3. Cancer in Experimental Animals

3.1 Oral administration

3.1.1 Mouse

Dietary exposure of diethylstilbestrol induced tumours in many sites, such as the ovary, endometrium and cervix of the uterus, and mesothelioma (origin not indicated) (Greenman *et al.*, 1986). Mammary adenocarcinoma incidence was increased in C3H/HeN-MTV+ female mice (Greenman *et al.*, 1987). Dietary diethylstilbestrol induced thyroid follicular cell adenoma in C57BL/6 mice (Greenman *et al.*, 1990).

Diethylstilbestrol was considered negative in the oral studies in Tg.AC mouse, which is one of the models selected for examination by topical application of either mutagenic or non-mutagenic carcinogens with papilloma formation at the site of application (Eastin *et al.*, 2001). Effect of dietary diethylstilbestrol was studied in $p53^{\pm}$ mice. Interstitial cell hyperplasia and tumours were observed in the testis, and pituitary hyperplasia and adenomas were observed in females; however, the incidences of these lesions were not statistically significant (Storer *et al.*, 2001). When, diethylstilbestrol was given to CB6F1-rasH2 transgenic mice, benign tumours and hyperplasia of the Leydig cells in the testes were noted. The incidence of Leydig cell tumours in the rasH2 males at high dose was significantly higher than in vehicle control males (4/15 vs 0/15; $P < 0.05$) (Usui *et al.*, 2001). Carcinogenicity of dietary diethylstilbestrol was investigated in two mouse knockout models, the Xpa homozygous knockout, and the combined Xpa homozygous and p53 heterozygous knockout. The incidence of osteosarcoma and testicular interstitial cell adenomas was higher in male Xpa/p53 mice. One Xpa male had osteosarcoma, which was not observed in wild-type mice. Xpa mice were no more sensitive than wild-type mice for compounds like diethylstilbestrol. The Xpa/p53 mouse model nevertheless showed an increased susceptibility to diethylstilbestrol in inducing osteosarcoma and testicular cell adenoma in males (McAnulty & Skydsgaard, 2005).

See Table 3.1.

3.2 Subcutaneous and/or intramuscular administration

3.2.1 Mouse

The effects of diethylstilbestrol on urethan-induced mouse lung carcinogenesis were assessed. Results indicate that diethylstilbestrol promotes lung carcinogenesis (Jiang *et al.*, 2000).

See Table 3.2.

Table 3.1 Studies of cancer in experimental animals exposed to diethylstilbestrol (oral exposure)

Species, strain (sex) Reference	Number/group at start, dose in diet, duration	Incidence of tumours	Significance	Comments
Mouse C3H/HeN-MTV(F) Greenman *et al.* (1986)	144, 912 controls 640 ppb DES in diet from 3, 5, 7, 9 wk of age (for 2, 4, 6, 8, 10, 12 wk or until 133 wk of age) DES-free diet for controls	*Ovary (granulosa cell tumours)* : Control : 16/75 (21%) DES : 1/181 (1%); 24/180 (13%); 44/183 (24%); 59/183[a] (32%)	[$P < 0.0001$][a]	Age at the start of DES treatment was a major factor in susceptibility of mice to mammary carcinogenesis of C3H/HeN-MTV- female mice
		Pituitary (adenoma) Control: 1/67 (1%) DES: 8/173 (5%); 10/180 (6%); 16/180 (9%); 21/179[b] (12%)	[$P < 0.0065$][b]	
		Uterus (endometrial carcinoma) Control : (0/77) DES : 0/182; 6/189 (3%); 9/191[c] (5%); 8/192 (4%)	[$P < 0.0449$][c]	
		Uterus (cervical carcinoma) Control : (0/77) DES : 0/182; 5/189 (3%); 13/191[d] (7%); 9/192[e] (5%)	[$P < 0.05$][d,e]	
		Mesothelioma[l] Control: (0/77) DES: 0/182; 13/189 (7%); 28/191 (5%); 29/192[f] (15%)	[$P < 0.0001$][f]	
		Mammary gland (adenocarcinoma) Control: (0/73) DES: 0/182; 0 189; 4/185 (2%); 3/182 (2%)		
Mouse C3H/HeN-MTV(F Greenman *et al.* (1987)	48–72, 312 controls 320 ppb DES in diet for 4, 8, 26 and 140 wk 640 ppb DES in diet for 4, 8, 26, and 140 wk DES-free diet for controls for 61 wk	*Mammary adenocarcinoma* Control: 234/295 (79%) 320 ppb: 59/71 (83%); 60/72 (83%); 69/72[a] (96%); 68/72[a] (94%) 640 ppb: 45/48 (94%); 46/48[a] (96%); 46/48[a] (96%); 47/48[a] (98%)	[$P < 0.05$][a]	
Mouse C57BL/6 (M/F) Greenman *et al.* (1990)	72 mice/sex/group DES 0, 5, 10, 20, 40, 160, 320, 640 ppb for 153 wk (male) or 143 wk (female) DES-free diet for controls	*Thyroid follicular cell adenomas* Male – 2/48 (4%); 0/51; 1/47 (2%); 3/48 (6%); 6/51 (11%); 27/51 (50%); 3/58 (5%); 0/43 Female – 13/64 (20%); 11/56 (20%); 10/51 (20%); 10/55 (18%); 16/61 (26%); 14/48 (29%); 4/60 (7%); 0/50	Male $P < 0.001$ (negative trend) Female $P < 0.001$ (negative trend)	

Table 3.1 (continued)

Species, strain (sex) Reference	Number/group at start, dose in diet, duration	Incidence of tumours	Significance	Comments
Mouse Tg.AC[2] (M/F) Eastin *et al.* (2001)	15 mice/sex/group DES 0, 30, 240, or 480 µg/kg bw in corn oil i.g. twice weekly for 26 wk then once during Week 27; control corn oil, 27 wk	No effect on the incidences of either forestomach papillomas or skin tumours in either sex.		No table available because of negative data
Mouse p53[±] transgenic (M/F) Storer *et al.* (2001)	15 mice/sex/group *Male* p53[±] (0, 50, 250 ppm), wild type (0, 50, 250 ppm), 26 wk *Female* p53[±] (0, 500, 1 000 ppm), wild type (0, 500, 1 000 ppm), 26 wk	*Male, testis (Interstitial cell tumour)* p53[±]: 0/15; 0/15; 2/15 (13%), wild type: 0/15; 0/13; 0/15 *Female, pituitary adenoma* p53[±]: 0/15; 2/15 (13%); 2/15 (13%), wild type: 0/15; 0/15; 0/14	Incidences of interstitial cell and pituitary tumours were not statistically significant	
Mouse CB6F1-rasH2 transgenic Usui *et al.* (2001)	15 mice/sex/group *Male* rasH2 (0, 0.1, 0.3, 1.0 ppm), wild type (0, 0.1, 0.3, 1.0 ppm), 26 wk *Female* rasH2 (0, 0.1, 0.3, 1.0 ppm), wild type (0, 0.1, 0.3, 1.0 ppm), 26 wk	*Male, Leydig cell tumour* rasH2: 0/15; 0/14; 0/15; 4/15[a] (27%), wild type: 0/15; 0/15; 1/15 (7%); 2/15 (14%) *Female, lung adenoma* rasH2: 1/14 (7%); 0/14; 4/14 (28%); 2/14 (14%), wild type: NR	[a] $P < 0.05$	

Table 3.1 (continued)

Species, strain (sex) Reference	Number/group at start, dose in diet, duration	Incidence of tumours	Significance	Comments
Mouse Xpa/p53[4] (M/F) McAnulty & Skydsgaard (2005)	15 mice/sex/group *Male* Xpa (0, 100, 300, 1500 ppb), wild type (0, 1500 ppb) Xpa/p53 (0, 1500 ppb) 39 wk *Female* Xpa (0, 100, 300, 1 500 ppb), wild type (0, 1 500 ppb) Xpa/p53 (0, 1 500 ppb) 39 wk	*Male, osteosarcoma* Xpa: 0/15; 0/14; 0/13; 1/6 (17%) wild type: 0/15; 0/15 Xpa/p53: 0/13; 5/6[a] (83%) *Male, testicular interstitial cell adenoma* Xpa: 0/15; 0/14; 3/13 (23%); 1/6 (17%) wild type: 0/15; 1/15 (7%) Xpa/p53: 0/13; 4/6[b] (67%) *Female, osteosarcoma* Xpa: 0/15; 0/15; 0/15; 0/2 wild type: 0/15; 0/15 Xpa/p53: 0/13; 2/2 (100%) *Female, mammary carcinoma* Xpa: 0/15; 0/15; 0/15; 0/2 wild type: 0/15; 0/15 Xpa/p53 1/13 (8%); 0/2	 $P < 0.05$[a] $P < 0.05$[b]	

[1] Origin was not described [2]The Tg.AC genetically engineered mouse, carrying a v-Ha-ras oncogene fused to the promoter of the gamma-globin gene [3]CB6F1-rasH2 transgenic mice with human c-Ha-ras proto-oncogene [4]Xpa homozygous and p53 heterozygous deficient condition
d, day or days; DES, diethylstilbestrol; F, female; i.g., intragastric; M, male; NR, not reported; wk, week or weeks

3.3 Subcutaneous implantation

3.3.1 Rat

Diethylstilbestrol pellets were implanted in lactating Wistar-MS rats after irradiation (260 cGy). A significantly higher incidence of mammary tumours was observed in the 260 cGy plus diethylstilbestrol group compared with the 260 cGy-alone group. The latency period was shortest in the diethylstilbestrol-treated group irradiated during the late lactation period. Diethylstilbestrol treatment alone in virgin rats, without irradiation (n = 20), did not produce any tumours (Suzuki *et al.*, 1994).

Implanted diethylstilbestrol silastic tubes induced significantly larger and highly haemorrhagic pituitary tumours in female F344 rats but not in Brown Norway (BN) rats. The female F1 (F344 x BN) rats exhibited significantly increased pituitary growth after 10 weeks of diethylstilbestrol treatment, but the pituitary was not haemorrhagic. The haemorrhagic pituitaries in F2 rats were mostly massive, indicating that some genes regulate both phenotypes (Wendell *et al.*, 1996). Diethylstilbestrol increased pituitary mass to 10.6-fold in male ACI rats, and only to 4.4-fold in male Copenhagen (COP) rats. The pituitary growth response of the diethylstilbestrol-treated (5 mg at 63 ± 4 days until 12 weeks of age) in F1 (COPxACI) rats was intermediate (6.9-fold) to that exhibited by the parental ACI and COP strains (Strecker *et al.*, 2005).

See Table 3.3.

3.4 Perinatal exposure

3.4.1 Mouse

Methylcholanthrene treatment induced vaginal tumours (squamous cell carcinoma and mixed (squamous cell carcinoma plus adenocarcinoma) carcinoma) with significantly higher incidence in the CD-1 mice after prenatal exposure to diethylstilbestrol (Walker, 1988). Prenatal exposure to diethylstilbestrol with a high-fat diet increased the incidence of uterine glandular tumours but not of mammary tumours (Walker, 1990). Prenatal diethylstilbestrol induced pituitary tumours in female CD-1 mice (Walker & Kurth, 1993).

In the CBA female descendants of mothers treated with prenatal diethylstilbestrol exposure, described as F2m, the incidence of uterine sarcomas, lymphomas, and ovarian tumours was significantly higher than in controls (Turusov *et al.*, 1992). The persistence of diethylstilbestrol effects was studied further one generation (diethylstilbestrol-lineage-2 mice). Diethylstilbestrol-lineage-2 mice, exposed to low- or high-fat maternal diets, had significantly more tumours in their reproductive system and liver than control mice with the same dietary fat exposure (Walker & Haven, 1997). The incidence of uterine adenocarcinomas in F2 females with prenatal diethylstilbestrol exposure was significantly higher than controls, whereas the incidence of tumours of the liver, lung or other organs examined in this study was not significantly different from that in control animals (Newbold *et al.*, 1998). In F2 males, a significant increase in the incidences of proliferative lesions of the rete testis (hyperplasia and tumours) was observed, suggesting that the rete testis is a target for the transgenerational effects of diethylstilbestrol in males (Newbold *et al.*, 2000).

Prenatal diethylstilbestrol treatment of female CBA mice increased the incidence of DMH-induced colon carcinoma (Turusov *et al.*, 1997). Effects of perinatal diethylstilbestrol exposure on mammary tumorigenesis were studied in female C3H/HeN/MTV+ mice. Neonatal treatment with a low dose of diethylstilbestrol increased the probability of mammary tumour formation (Lopez *et al.*, 1988). Effects of perinatal exposure to estrogens during the developing stage of reproductive tract organs were studied in CD-1 mice. Uterine adenocarcinomas were induced in a time- and dose-related manner

Table 3.2 Studies of cancer in experimental animals exposed to diethylstilbestrol (intramuscular injection)

Species, strain (sex) Reference	Number/group at start, dose, duration	Incidence of tumours, multiplicity	Significance	Comments
Mouse Kunming (F) Jiang *et al.* (2000)	26–28, 58 controls Single i.p. injection of U in saline (50 mg/kg) + DES, i.m. injections one wk later 5 or 50 mg/kg bw once every wk for 18 wk Control: saline and DMSO + saline	*Lung macroscopic tumours* U alone (9/27 (33%), 0.69 ± 1.04) U + DES 5 mg (17/28[a] (61%), 1.80 ± 1.79[b]) U + DES 50 mg (20/26[b] (77%), 3.81 ± 2.83[b]) *Lung malignant tumour*[1] U alone (5/27) (18%) U + DES 5 mg (9/28) (32%) U + DES 50 mg (17/26[b]) (65%)	$P < 0.05$[a, b], $P < 0.01$ vs U alone group, respectively	DES is a promoter of lung carcinogenesis. Age at start NR, animal weight 17–20 g

[1] Malignant tumours were combinations of adenocarcinoma, papillocarcinoma (author's translation), and mixed type cancer

DES, diethylstilbestrol; i.m., intramuscular; i.p., intraperitoneal; NR, not reported; U, urethane; wk, week or weeks

Table 3.3 Studies of cancer in experimental animals exposed to diethylstilbestrol (subcutaneous implantation)

Species, strain (sex) Reference	Number/group at start, dose, duration	Incidence of tumours, multiplicity	Significance	Comments
Rat Wistar-MS (F) Suzuki *et al.* (1994)	17–28 rats/group Irradiated with 260 cGy of gamma rays on 21 d after parturition[1] + CHOL pellets containing 5 mg DES were implanted 1 mo after lactation. DES pellets[2] remained for 1 yr and were replaced every 8 wk	Mammary tumours (no histological information) *Incidence, latency period (month)* 260 cGy + CHOL (6/17 (35%), 10.5 ± 0.2); O cGy + DES (3/11 (27%), 10.0 ± 1.2); 260 cGy + DES (27/28 (96%), 7.4 ± 0.5); Virgin rats: 0 cGy + DES (0/20)	$P < 0.001$ in the incidence and latency period, 260 cGy + DES vs 260 cGy + CHOL $P < 0.001$ in the incidence and latency period 260 cGy + DES vs DES alone	DES promoted radiation-induced mammary tumorigenesis

[1] Detailed location was not described [2] The release of DES from the pellet was estimated to be 1 µg/day

CHOL, cholesterol; d, day or days; DES, diethylstilbestrol; F, female; mo, month or months; wk, week or weeks

after diethylstilbestrol treatment (Newbold *et al.*, 1990). Male offspring of CD-1 mice with transplacental exposure to arsenite were treated with diethylstilbestrol neonatally. Total liver tumour incidence, the number of mice with multiple liver tumours, and urinary bladder proliferative lesions was higher in the arsenite plus diethylstilbestrol mice compared to the arsenite-alone group (Waalkes *et al.*, 2006b). In female offspring CD-1, the incidence of carcinoma of the cervix and of urinary bladder total proliferative lesions (hyperplasia plus papilloma plus carcinoma) in the arsenite plus diethylstilbestrol group was significantly higher than in the arsenite-alone group (Waalkes *et al.*, 2006a).

CD-1 and diethylstilbestrol induced-TGFα transgenic mice were neonatally treated with diethylstilbestrol. The presence of the TGFα transgene significantly increased the incidence of endometrial hyperplasia and benign ovarian cysts, whereas it did not promote uterine adenocarcinoma (Gray *et al.*, 1996). Transgenic MT-mER mice, which overexpress the estrogen receptor, driven by the mouse metallothionein I promoter, were neonatally treated with diethylstilbestrol. The diethylstilbestrol-treated MT-mER mice demonstrated a significantly higher incidence of uterine adenocarcinomas (Couse *et al.*, 1997). Diethylstilbestrol-treated wild-type mice exhibited a relatively high frequency of uterus endometrial hyperplasia and granulosa cell tumours in the ovary, while αERKO mice (estrogen receptor α knockout mice) showed a complete lack of these lesions (Couse *et al.*, 2001). Lymphoma-prone Mlh1 or Msh2 knockout mice were treated with diethylstilbestrol. Combination of Mlh1 deficiency condition with diethylstilbestrol exposure was shown to accelerate lymphomagenesis (Kabbarah *et al.*, 2005). Murine PTEN (mPTEN) heterozygous mutant mice demonstrated that neonatal diethylstilbestrol treatments exerted an inhibitory, rather than an enhancing, effect on PTEN-associated endometrial carcinogenesis via stromal alterations (Begum *et al.*, 2006).

3.4.2 Rat

Mammary tumours are induced in female ACI rats by either prenatal injections or by postnatal pellet implantation of diethylstilbestrol. The combination of both yielded significantly greater tumour multiplicity, and decreased tumour latency (Rothschild *et al.*, 1987). Vaginal epithelial tumours were induced in a dose-related manner in female Wistar rat following in-utero diethylstilbestrol exposure (Baggs *et al.*, 1991). Prenatal exposure to diethylstilbestrol produced uterine adenocarcinomas and pituitary adenomas in female Donryu rats, as reported in an earlier study in mice (Kitamura *et al.*, 1999). In Sprague Dawley rats, neonatal diethylstilbestrol exposure at a relatively low dose (1 μg/kg bw) caused an increase in the incidence of mammary carcinomas induced by 1,2-dimethylbenz[*a*] anthracene (Ninomiya *et al.*, 2007). Female rats carrying the Eker mutation (*Tsc-2*$^{Ek/+}$) administered diethylstilbestrol neonatally had a significantly greater multiplicity of leiomyoma in the uterus (Cook *et al.*, 2005).

3.4.3 Hamster

The subcutaneous implantation of diethylstilbestrol pellets caused renal tumours in young Syrian hamsters (Liehr & Wheeler, 1983), and diethylstilbestrol pellets, implanted after orchiectomy, induced kidney tumours in the same species (Goldfarb & Pugh, 1990). Diethylstilbestrol-treated castrated hamsters exhibited interstitial lesions in the kidney as well as kidney tumours (Oberley *et al.*, 1991). In male and female Armenian hamsters, diethylstilbestrol pellets applied subcutaneously induced hepatocellular carcinomas (Coe *et al.*, 1990).

See Table 3.4.

3.5 Synthesis

The oral administration of diethylstilbestrol induced tumours of the ovary, endometrium and cervix, and mammary adenocarcinomas in female mice. Osteosarcomas and Leydig cell tumours were induced in rasH2 and Xpa/p53 male mice, respectively.

Subcutaneous implantation of diethylstilbestrol induced mammary tumours in female Wistar rats.

Perinatal exposure to diethylstilbestrol induced lymphomas, uterine sarcomas, adenocarcinomas and pituitary, vaginal, and ovarian tumours in female mice. Uterine adenocarcinomas and mammary and vaginal tumours were also induced in female rats. In hamsters, diethylstilbestrol perinatal exposure induced kidney tumours. In castrated hamsters, kideney tumours were also induced following implantation of diethylstilbestrol.

4. Other Relevant Data

4.1 Absorption, distribution, metabolism, and excretion

The toxicokinetics and metabolism of diethylstilbestrol (diethylstilbestrol) were reviewed in 1979 (IARC, 1979b), and by Metzler & Fischer (1981).

Diethylstilbestrol is readily absorbed and distributed in the whole organism after oral administration (Marselos & Tomatis, 1992). In animal models used for the pharmacokinetics of diethylstilbestrol (with the exception of primates), it is apparent that the drug is almost exclusively eliminated through biliary excretion into the intestine, where it undergoes extensive enterohepatic circulation before being excreted in the faeces (Marselos & Tomatis, 1992). Only traces of diethylstilbestrol can be detected in urine (McMartin *et al.*, 1978).

Whole animal autoradiography experiments showed that radiolabelled diethylstilbestrol injected intravenously into rats is accumulated in the liver and small intestine within 4 hours, and radioactivity can still be detected in these organs after 4 days (Bengtsson, 1963). Peak plasma levels of radioactivity were found within 16 hours in sheep given radiolabelled diethylstilbestrol at single oral doses. Radioactivity disappeared almost completely after 120 hours (Aschbacher, 1972). Ten days after a single oral dose of radiolabelled diethylstilbestrol to steers, residues could be detected in the small intestine, the faeces, and the urine (Aschbacher & Thacker, 1974). In the rat, it was demonstrated that after intestinal intubation of diethylstilbestrol or diethylstilbestrol-glucuronide, free diethylstilbestrol is readily absorbed through the epithelium, whereas the conjugated form requires prior hydrolysis by the intestinal microflora (Fischer *et al.*, 1973).

Studies on diethylstilbestrol transfer across the placenta in mice have shown that it accumulates in the fetal genital tract, where it reaches levels 3 times higher than found in the fetal plasma (Shah & McLachlan, 1976).

The kinetics of a single oral dose of radiolabelled diethylstilbestrol (10 mg) in cattle followed a biphasic depletion curve, attributed to hepatic clearance. An initial steeper slope represented a biological half-life of 17 hours, while the half-life for the later phase was 5.5 days (Rumsey *et al.* 1975a). Furthermore, pellets of 24–36 mg diethylstilbestrol implanted subcutaneously in cattle or steers liberated about 56–74 µg of diethylstilbestrol per day into the circulation; the half-life was 80–90 days (Rumsey *et al.* 1975b).

Subsequently, the oxidative quinone metabolite of diethylstilbestrol (4',4''-diethystilbestrol quinone) was found to be reactive *in vitro*, binding to DNA (Liehr *et al.*, 1983; 1985a). The formation of the quinone is mediated by microsomal monooxygenase (Degen *et al.*, 1986; Roy *et al.*, 1991a), in particular cytochrome P450(CYP)1A1 (Roy *et al.*, 1992), by prostaglandin synthase

Table 3.4 Studies of cancer in experimental animals exposed to diethylstilbestrol (perinatal exposure)

Species, strain (sex), age Reference	Number/group at start Route, dose, duration	Incidence of tumours	Significance	Comments
Mouse CD-1 (F), gestation Day 17 Walker (1988)	Number/group at start NR Prenatal: s.c. injection 1 µg/g bw DES in olive oil + 2% ethanol at Day 17 of pregnancy + Postnatal: sponges impregnated with MCA in beeswax were lodged against the cervix and vaginal fornices of the mice at 6 months of age Controls received olive oil	*Vaginal tumours:* *(SCC and mixed (SCC + adenocarcinoma) carcinoma)* DES + MCA (10/35, 29%) Vehicle + MCA (2/28, 7%) DES + beeswax (1/12, 8%) Vehicle + beeswax (0/8, 0%)	$P < 0.05$ DES+MCA vs Vehicle+MCA	
Mouse CD-1 (F), gestation Day 16 Walker & Kurth (1993)	Up to 14 mo 132; 64 controls i.p. injection 1 or 2 µg/g bw at 16–17 days postconception For life	*Pituitary tumours:* Control (1/57, 2%) DES 1 µg (19/34, 56%) DES 2 µg (3/3, 100%)	$P < 0.01$	
Mouse CBA (F), gestation Day 17 Turusov *et al.* (1992)	Number/group at start NR Prenatal: i.p. injection 1 µg/g bw DES in olive oil + 2% ethanol at Day 17 of pregnancy (F2m,[1] the descendants of DES-treated grandmothers were used in this study) For life	*Uterine sarcomas:* F2m female (17/84, 20%), control (6/108, 6%) *Lymphomas:*[2] F2m female (17/84, 20%), control (10/108, 9%) *Benign ovarian tumours:* F2m female (16/84, 19%), control (9/108, 8%)	$P = 0.0022$ $P = 0.037$ $P = 0.004$	

Table 3.4 (continued)

Species, strain (sex), age Reference	Number/group at start Route, dose, duration	Incidence of tumours	Significance	Comments
Mouse CD-1 (F), gestation Day 17 Walker & Haven (1997)	Number/group at start NR 1 µg/g bw of DES in olive oil + 0.1% ethanol at Day 17 of pregnancy. DES-lineage2[3] mice were exposed to low- (LF, 2.6%) or high-fat (HF, 29%) diets For life	*Reproductive system tumours:* *Combination of ovarian, uterine, cervical (adenocarcinoma)* *and mammary tumours (adenocarcinoma + sarcoma)* DES+LF (31/61, 51%), LF (11/66, 17%) DES+HF(25/54, 46%), HF (18/68, 26%) *Liver tumours:* DES+LF (17/61, 28%), LF (32/66, 48%) DES+HF (16/54, 30%), HF (22/68, 32%)	 $P < 0.001$ $P < 0.05$ $P = 0.03$ NS	The multigenerational effect of DES was observed in mice
Mouse CD-1 (F), Day 1 for F2 Newbold *et al.* (1998)	Number at start NR s.c. injection G1: 2.5, 5, 10 µg/kg bw on Days 9–16 of gestation G2: 1000 µg/kg bw on Day 18 of gestation G3: 0.002 µg/pup/day on Days 1–5 after birth Female F2 mice[4] were examined in this study. Animals were held for 17–19 or 22–24 mo	*Uterine adenocarcinomas in F2:* Groups / at 17–19 mo / at 22–24 mo / total Control: 0/32 / 0/23 / 0/55 G1 2.5 g: 2/29 (7%) / 3/35 (9%) / 5/64 (8%) G1 5 g: 2/35 (6%) / 6/37 (16%) / 8/72 (11%) G1 10 g: 0/16 / 0/24 / 0/40 G2: 0/33 / 1/15 (7%) / 1/48 (2%) G3: 1/29 (3%) / 4/36 (11%) / 5/65 (8%)	vs. concurrent controls;[5] vs. historical controls[6] – ; – $P < 0.05$; $P < 0.001$ $P < 0.01$; $P < 0.001$ NS; NS NS; NS $P < 0.05$; $P < 0.001$	Pups, 1–3.5 g

Table 3.4 (continued)

Species, strain (sex), age Reference	Number/group at start Route, dose, duration	Incidence of tumours	Significance	Comments
Mouse CD-1 (M) Day 1 for F2 Newbold *et al.* (2000)	Number at start NR s.c. injection G1: 2.5, 5, 10 g/kg bw on Days 9–16 of gestation G2: 1000 µg/kg bw on Day 18 of gestation G3: 0.002 µg/pup/d on Days 1–5 after birth DES was dissolved in corn oil Male F2 mice[7] examined in this study were killed at 17–24 mo	*Rete testis proliferative lesions (hyperplasia or tumours) in testis of DES-lineage (F2) male mice:* Control (3/53, 6%) G1 2.5 µg (15/73, 21%) G1 5 µg (27/83, 32%) (1 tumour) G1 10 µg (17/49, 35%) G2 (5/52, 10%) (1 tumour) G3 (7/23, 30%)	– $P < 0.05$ $P < 0.01$ $P < 0.01$ NS $P < 0.01$	Pups, 1–3.5 g
Mouse, C3H(F) CBA(F) 2–3 months for F1 Turusov *et al.* (1997)	35–50; 84–101 controls/group s.c. injection 0, 0.1, 0.3 mg/kg bw DES in olive oil + 0.1% ethanol at Day 17 of pregnancy and then descendants were treated with 1,2-dimethyl hydrazine (DMH)[8] Killed at Week 50 after the beginning of DMH	*Colon carcinomas:* DMH / 0.1-DES+DMH / 0.3-DES+DMH C3H: 9/37 (24%) / 6/45 (13%) / 4/32 (12%) — NS CBA: 2/38 (5%) / 10/54 (18%) / 10/27 (37%) — P<0.01 (0.3–DES+DMH) *Uterus sarcomas:* C3H: 0/37 / 4/45 (9%) / 0/32 — NS CBA: 21/38 (55%) / 29/54 (53%) / 16/27 (59%) — NS		
Mouse CD-1 (F) Day 1 of life Newbold *et al.* (1990)	Number at start NR s.c. injection of 0.002 or 2 µg/pup/d DES in corn oil for Days 1–5 of age Controls received corn oil Killed 1, 2, 4, 6, 8, 12, 18 mo of age	*Uterus adenocarcinomas of 2 µg group at 1, 2, 4, 6, 8, 12, 18 mo:* DES: 0/18, 0/10, 0/10, 0/12, 0/5, 8/17 (47%), 9/10 (90%) Controls: 0/15, 0/10, 0/10, 0/12, 0/5, 0/17, 0/10	$P = 0.0026$ at 12 mo, $P = 0.0002$ at 18 mo	

Table 3.4 (continued)

Species, strain (sex), age Reference	Number/group at start Route, dose, duration	Incidence of tumours	Significance	Comments
Mouse CD-1 (F) Day 1 of life (female offspring) Waalkes *et al.* (2006a)	35 animals/group (offspring) Transplacental exposure to arsenite (ARS)[9] 85 ppm from Days 8–18 of gestation + s.c. injection 2 µg/pup/d DES Days 1–5 of age Killed at 90 wk	*Cervix (carcinoma):* Control (0/33), ARS (0/34), DES (6/33, 18%), ARS+DES (8/33, 24%) *Urinary bladder (total proliferative lesions):*[10] Control (1/33, 3%), ARS-alone (5/34, 15%), DES-alone (1/33, 3%), ARS+DES (13/33, 38%)	$P = 0.01$ (DES vs control) $P < 0.05$ (ARS+DES vs ARS) $P < 0.05$ (ARS+DES vs ARS)	Sodium arsenite in the drinking-water
Mouse CD-1(F) TGF α[11](F) Day 1 of life Gray *et al.* (1996)	Number/group at start NR s.c. injection 2 µg/pup/d DES in sesame oil on Days 1 – 5 of age Control remained untreated maintained 39, 52 wk or for life	*Uterus (adenocarcinoma):* Vehicle in CD-1, (0/26) Vehicle in TGF α (0/25) DES in CD-1 (7/16, 44%) DES in TGF α (7/15, 47%)	– – $P<0.01$ $P<0.01$	
Mouse, Wild type fvb/N (F) MT-mER[12] (F) Day 1 of life Couse *et al.* (1997)	Number/group at start NR s.c. injection 2 µg/pup/d DES in corn oil on Days 1 – 5 of age Control: untreated Killed at 4, 8, 12, and 18 mo of age	*Uterus adenocarcinomas at 4, 8, 12, 18 mo:* MT-mER +DES: 0/19, 19/26 (73%), 13/15 (87%), 12/13 (92%) Wild type+DES: 0/19, 11/24 (46%), 11/15 (73%), 13/14 (93%) MT-mER control: 0/14, 0/10, 0/15, 1/19 (5%) Wild type control: 0/15, 0/11, 0/15, 0/19	$P < 0.05$ at 8 months (MT-mER+DES vs Wild type+DES) $P < 0.05$ at 8, 12, 18 mo (Wild type+DES vs wild type)	
Rat, ACI (F) gestation Day 15 Rothschild *et al.* (1987)	32–47, 32 controls Prenatal: s.c. injection of 0.8 µg (Low) or 8.0 µg (High) DES in sesame oil on Days 15 and 18 of gestation Postnatal:[13] 2.5 mg DES pellet at 12 wk Control: sesame oil (vehicle/DES) Killed 7 mo post pellet	*Mean time to appearance of first mammary tumour, mean No. of palpable mammary tumours/rat:* Vehicle/DES: 22.2 wk, 2.2 Low DES/DES: 19.4 wk[a], 3.0 High DES/DES: 15.2 wk[a], 4.3[b]	 [a] $P < 0.05$ vs Vehicle/DES [b] $P < 0.05$ vs Vehicle/DES	
Rat, Wistar (F) gestation Day 18 Baggs *et al.* (1991)	11–80, 147 controls i.p. injection 0, 0.1, 0.5, 25, 50 mg/kg bw on Days 18, 19, and 20 of gestation > 120 days	*Vaginal epithelial tumours:*[14] 2/147 (1%), 2/49 (4%), 4/80 (5%), 1/63 (2%), 3/11 (27%)	$P < 0.001$ (dose response)	

Table 3.4 (continued)

Species, strain (sex), age Reference	Number/group at start Route, dose, duration	Incidence of tumours	Significance	Comments
Rat, Donryu (F) gestation Day 17 Kitamura *et al.* (1999)	35–72, 23 controls s.c. injection 0, 0.01, 0.1 mg/kg bw DES on Days 17 and 19 of gestation Control: olive oil 18 months	*Uterus tumours:* *(endometrial adenocarcinoma)* 1/20 (5%), 4/39 (10%), 9/29 (31%) *Pituitary adenomas:* 1/20 (5%), 0/39, 6/29 (20%)	$P < 0.05$, 0.1 mg vs control $P < 0.01$, 0.1 mg vs control	
Rat, Sprague Dawley (F) Day 1 of life Ninomiya *et al.* (2007)	13–21, 22 controls s.c injection 0, 0.1, 1, 10, 100 µg/kg bw DES in sesame oil at birth. 50 days after birth all rats received 1 mg DMBA in 1 mL sesame oil by gastric intubation Killed 50–300 d after birth	*Mammary tumour incidence and multiplicity (Mammary adenocarcinoma) at 300 d after birth:* 0.0 µg: 17/22 (77%), 1.50 ± 1.19 0.1 µg: 13/15 (86%), 2.80 ± 1.61[a] 1 µg: 21/21[a] (100%), 3.00 ± 1.22[b] 10 µg: 11/13 (85%), 2.54 ± 1.66[a] 100 µg: 12/16 (75%), 1.63 ± 1.45	[a] $P < 0.05$ vs control [b] $P < 0.01$ vs control	
Rat Eker Rats carrying a germ-line defect in the tuberous sclerosis complex 2 (Tsc-2) tumour suppressor gene (F) Day 3 of life Cook *et al.* (2005)	Number at start NR s.c. injections 10 µg/rat/d DES in sesame oil on Days 3, 4, and 5 after birth Controls: 50 µl sesame oil Killed up to 16 mo of age.	*Uterus (leiomyoma):* *Incidence, multiplicity and size* In Ekar rats *Tsc-2*$^{Ek/+}$ Vehicle: 18/28 (64%), 0.82 ± 0.15, 2.30 ± 1.10 DES: 22/24 (92%), 1.33 ± 0.17[a], 10.50 ± 2.70[a] In wild type *Tsc-2*$^{+/+}$ Vehicle: 0/34, 0, 0 DES: 0/34, 0, 0	[a] $P < 0.02$ in multiplicity, and size in Eker rats (DES vs vehicle)	
Hamster Syrian (M), 4 wk Liehr & Wheeler (1983)	15 animals/group Two 40 mg pellets containing 90% DES + 10% cholesterol were implanted at Day 27 and one more (same composition) 3 mo later 172 d	*Renal tumours:* Control (0/9) DES (11/13, 85%)	$P < 0.05$	

Table 3.4 (continued)

Species, strain (sex), age Reference	Number/group at start Route, dose, duration	Incidence of tumours	Significance	Comments
Hamster, Syrian (M), 7 wk Goldfarb & Pugh (1990)	9–13; 8–12 controls Orchiectomy and 4 wk later 20 mg DES pellets every 3 mo, 2.5–6.2 mo	*Renal tumours:* Controls at 2.5–3; 5–6.2 mo 0/8; 0/12 DES at 2.5; 4.6; 5.6; 6.2 mo 0/13; 2/12 (17%); 8/12 (67%); 7/9 (78%)	$P < 0.05$, DES vs control at 6.2	
Hamster, Syrian (M) 2 mo Oberley *et al.* (1991)	57, 4 controls Castrated and 20 mg of DES pellet every 2.5 mo, for 1–9 mo	*Interstitial foci in the kidney:* DES at 1, 2, 3, 4, 5, 6, 7, 8, 9 mo 0/7; 0/7; 0/7; 0/7; 4/12 (33%); 5/8 (62%); NR; 2/3 (66%); 1/6 (17%) *Kidney tumours:*[13] DES at 1, 2, 3, 4, 5, 6, 7, 8, 9 mo 0/7; 0/7; 0/7; 0/7; 0/12; 3/8 (37%); NR; 2/3 (67%); 4/6 (67%) Controls: at 9 mo 0/4	NS	Age NR, Animal weight 90–100 g

[1] The descendants of DES-treated mothers, described as F1DES, were mated among each other or with untreated animals. F1DES males were successfully mated with untreated females (F2m). [2] Both grossly visible tumours and microscopic cancers included in this category. [3] The descendants of DES-treated mothers, described as DES-lineage were mated with control animals. DES-lineage2 mice were generated by mating DES-lineage female mice with control males. [4] Female mice (F1) in each group were raised to sexual maturity and bred with control males. Female offspring (DES lineage or F2) from these matings were raised to maturity and housed with control males for 20 weeks. [5] versus concurrent controls; relative to concurrent control rate of 0/55. [6] versus historical controls; relative to historical control rate of 0.4% (2/482) in 21–24 month old female Charles River CD-1 mice. [7] DES-exposed female mice (F(1)) were raised to maturity and bred with control males to generate DES-lineage (F(2)) descendants. The F(2) males obtained from these matings are the subjects of this report. [8] The descendants, starting from the age of 2–3 months, received weekly s.c. injections of 1,2-dimethylhydrazine (DMH) (8 mg/kg bw), for a total of 20 injections. [9] Pregnant CD-1 mice received 85 ppm arsenite in the drinking-water from gestation Days 8 to 18 [10] Total proliferative lesion (hyperplasia+ papilloma+ carcinoma). [11] Homozygous TGF α transgenic female mice from the MT42 line. [12] The transgenic construct consisted of a fragment of the mouse ER cDNA encoding the full-length ER protein driven by the mouse metallothionein I promoter. [13] Pellets containing 2.5 mg DES+17.5 mg cholesterol (DES pellet) or 20 mg cholesterol were implanted s.c. into 12-week-old female offsprings. [14] The types of epithelial tumours of the vagina were adenocarcinomas, squamous cell carcinomas, and mixed carcinomas

bw, body weight; d, day or days; DES, diethylstilbestrol; DMBA, 7,12 dimethylbenz[*a*]anthracene; F, female; i.p., intraperitoneal; M, male; MCA, methylcholanthrene; mo, month or months; NR, not reported; NS, not significant; s.c., subcutaneous; wk, week or weeks

(Ross *et al.*, 1985; Degen, 1993), and by peroxidases (Metzler, 1984; Liehr *et al.*, 1983; 1985a). The quinone metabolite is reduced by P450 reductase and xanthine oxidase, via the semiquinone and non-enzymatically, directly to diethylstilbestrol (Roy & Liehr, 1988; Roy *et al.*, 1991b). Diethylstilbestrol quinone is also formed *in vivo*, in the kidney of diethylstilbestrol-treated male Syrian hamsters (Roy & Liehr, 1988), in the mammary gland tissue of diethylstilbestrol-treated ACI rats (Thomas *et al.*, 2004), and in the liver of diethylstilbestrol-treated rats (Green *et al.*, 2003). Diethylstilbestrol quinone is formed in the liver, kidney, uterus, and placenta of pregnant diethylstilbestrol-treated Syrian hamsters, and in the liver and kidney of their fetuses (Roy & Liehr, 1989). Diethylstilbestrol metabolites are also found in the female genital tract of adult mice and pregnant mice, and in tissues of their fetuses (Gottschlich & Metzler, 1984; Maydl *et al.*, 1985). The quinone metabolite was found to undergo a CYP-mediated process of redox cycling (Liehr *et al.*, 1985a), via a semiquinone intermediate (Kalyanaraman *et al.*, 1989).

During redox cycling of diethylstilbestrol, superoxide radicals are formed *in vitro* (Epe *et al.*, 1986; Roy and Liehr, 1988). In the kidney of diethylstilbestrol-treated hamsters, elevated levels of 8-hydroxy-deoxyguanosine were found, indicating that diethylstilbestrol can induce oxidative DNA damage *in vivo* (Roy *et al.*, 1991c). Furthermore, increased levels of lipid hydroperoxides and of malondialdehyde-DNA adducts were also detected (Wang & Liehr, 1995a). Lipid hydroperoxides were also found to be increased in the mammary gland tissue of diethylstilbestrol-treated ACI rats (Gued *et al.*, 2003). These lipid hydroperoxides co-activate the CYP1A1-mediated oxidation of diethylstilbestrol to its quinone metabolite (Wang & Liehr, 1994). Diethylstilbestrol treatment reduced the activity of enzymes that protect against diethylstilbestrol-induced oxidative stress, such as glutathione peroxidase, quinone reductase, and superoxide dismutase (Segura-Aguilar *et al.*, 1990). In the mammary gland tissue of female rats, expression of *Cyp1A1* gene was increased by diethylstilbestrol treatment, whereas the expression of the genes encoding glutathione-*S*-transferase and superoxide dismutase were depressed (Green *et al.*, 2007).

The oxidative metabolism of diethylstilbestrol almost certainly plays a central role in the induction of kidney tumours in Syrian hamsters, of genetic changes in various in-vitro assays, and probably also of other tumours in animals perinatally exposed to diethylstilbestrol *in utero*. Whether these events occur in target tissues of transplacental exposure to diethylstilbestrol in humans has not been determined.

4.2 Genetic and related effects

4.2.1 Direct genotoxicity

(a) Humans

No changes in DNA ploidy pattern and no mutations were found in specific cancer-related genes (H-*RAS* and K-*RAS* proto-oncogenes, *TP53* and the Wilms' tumour (*WT-1*) tumour suppressor genes) or in the coding region of the *estrogen receptor-α* (*ERα*) gene (Welch *et al.*, 1983; Boyd *et al.*, 1996; Waggoner *et al.*, 1996). The frequency of some known polymorphisms (exon 1, 3, and 8) in the *ERα* gene was not different from that expected in the general population (Boyd *et al.*, 1996).

In cervico-vaginal biopsies and smears from 19 women who had been exposed to diethylstilbestrol *in utero* and 19 controls, the frequencies of trisomy of chromosomes 1, 7, 11, and 17 were evaluated by the FISH technique. The trisomy frequencies were elevated in 4/19 (21%) diethylstilbestrol-exposed women. Trisomy of chromosomes 1, 7, and/or 11 was found, which frequently occurs in gynaecological tumours, but trisomy of chromosome 17 did not occur. No

chromosomal trisomy was observed in samples from the control women (Hajek *et al.*, 2006).

In neoplastic and preneoplastic lesions of the breast, loss of heterozygosity and allelic imbalance at 20 microsatellite markers on nine chromosomal arms was comparable between women exposed *in utero* to diethylstilbestrol and control women (Larson *et al.*, 2006).

There are no data on the effects of diethylstilbestrol on cell proliferation or apoptosis in human target tissues of diethylstilbestrol-induced carcinogenicity.

Women with documented in-utero exposure to diethylstilbestrol had a higher mitogen-induced proliferation of peripheral blood lymphocytes compared to age- and menstrual-cycle phase-matched control women (Ways *et al.*, 1987; Burke *et al.*, 2001), suggestive of an increased cellular immune response. A hyperactive immune system may be related to the reported higher frequency of autoimmune disease, and immune-related inflammatory disorders such as arthritis following in-utero exposure to diethylstilbestrol, compared with control women (Wingard & Turiel, 1988; Noller *et al.*, 1988). However, natural killer-cell activity was not found to be altered in women exposed to diethylstilbestrol *in utero* (Ford *et al.*, 1983).

The developmental abnormalities and the disturbance of menstrual activity found in sons and daughters, respectively, of diethylstilbestrol daughters suggest that third generation (F2) effects of human prenatal diethylstilbestrol exposure, including cancer development, are conceivable. However, there are no mechanistic data on this point in animal models, nor data about germ-line mutations or other heritable alterations.

Vaginal adenosis is an established, although non-obligatory, precursor of clear cell adenocarcinoma. Although most women affected by vaginal adenosis do not develop clear cell adenocarcinoma, adenosis is present in up to 100% of women with clear cell adenocarcinoma (Herbst *et al.*, 1972; Herbst *et al.*, 1974; Robboy *et al.*, 1984a).

Other effects of in-utero exposure to diethylstilbestrol include infertility in female offspring, as reported in most but not all studies (Palmer *et al.*, 2001), and possibly in males (Perez *et al.*, 2005).

In most studies, changes in menstrual activity by decreasing the duration of menstrual bleeding were observed in comparison with control women (Hornsby *et al.*,1994). Young women whose mothers had been exposed to diethylstilbestrol *in utero* had a 1.5- to 2-fold increased risk for self-reported menstrual irregularities and fertility problems (Titus-Ernstoff *et al.*, 2006b).

In a meta-analysis (Martin *et al.*, 2008) of three studies (Klip *et al.*, 2002; Palmer *et al.*, 2005; Pons *et al.*, 2005), in-utero exposure to diethylstilbestrol was associated with a 3.7-fold increased risk for hypospadias in men.

(b) Experimental systems

(i) In vivo

Diethylstilbestrol induced chromosomal aberrations in bone-marrow cells of mice treated *in vivo*, but data on in-vivo induction of sister chromatid exchange and micronuclei were equivocal (IARC, 1987b); it induced sister chromatid exchange in one study in rats (Gloser & Cerni, 1984). Diethylstilbestrol induced micronuclei in early haploid mouse spermatids 17 days after a single subcutaneous injection (Pylkkänen *et al.*, 1991a); chromosomal aberrations in cells of the renal cortex in male Syrian golden hamsters (the target tissue of diethylstilbestrol-induced carcinogenicity) (Banerjee *et al.*, 1994); sister chromatid exchange (but no changes in chromosome number) in uterine cervical epithelial cells, but not in the epithelium of the uterus or kidneys (Forsberg, 1991), and sister chromatid exchange, but no aneuploidy in mouse bone-marrow cells (Zijno *et al.*, 1989). Markedly increased aneuploidy was found in proximal tubular kidney

cells of male Syrian hamsters with subcutaneously implanted diethylstilbestrol pellets (Li *et al.*, 1993; 1999).

In hamsters, diethylstilbestrol-induced kidney tumours point mutations were detected in the catalylic domain of DNA polymerase β gene compared to control normal tissue (Yan & Roy 1995), and at 44/365 random loci, seven of which were also present in non-tumorous kidney tissue (Singh & Roy, 2004). The expression of DNA polymerase β and a novel gene, *Etrg-1*, was reduced in tumorous and non-tumorous kidney tissues of diethylstilbestrol-treated hamsters compared to controls (Singh & Roy, 2008). Microsatellite instability was increased in early lesions induced by neonatal treatment of mice (Kabbarah *et al.*, 2003). In host-mediated assays using mice, no DNA-repair response was detected in *E. coli* strains (Kerklaan *et al.*, 1986).

Using [^{32}P]-postlabelling, adducted nucleotides were found in the kidney DNA of hamsters chronically treated with diethylstilbestrol but not in the kidneys of untreated animals (Liehr *et al.*, 1985b). Some adducts were chromatographically identical to those induced by estradiol and other estrogenic compounds, suggesting that some of these adducts may not be diethylstilbestrol-derived (Liehr *et al.*, 1986). The major diethylstilbestrol adduct formed *in vivo* in the hamster kidney and liver DNA was chromatographically identical to that observed after in-vitro reaction of DNA with 4',4''-diethystilbestrol quinone in the presence of microsomes and hydroperoxide cofactors, suggesting that this metabolite is responsible for DNA damage by diethylstilbestrol *in vivo*, and that oxidative metabolism of diethylstilbestrol is required for its formation (Bhat *et al.*, 1994; Gladek & Liehr, 1989). The adduct was unstable with an in-vitro half-life of 4–5 days at 37°C, and an estimated in-vivo half-life of 14 hours, which is suggestive of in-vivo repair (Gladek & Liehr, 1989). Importantly, diethylstilbestrol adducts were also found in the mammary gland tissue of diethylstilbestrol-treated adult female rats (Green *et al.*, 2005), and in hamster fetal tissues after injection of their mothers with diethylstilbestrol, but the major adduct found was different from that identified in the kidneys of adult diethylstilbestrol-treated hamsters (Gladek & Liehr, 1991). The precise structures of the diethylstilbestrol-induced DNA adducts have not been elucidated, but it is probable that some are oxidative-stress-generated lipid-hydroperoxide- and malondialdehyde-DNA adducts (Wang & Liehr, 1995a; 1995b). Although feeding of vitamin C reduced the incidence of kidney tumours, the generation of diethylstilbestrol quinone, and the formation of adducts in the kidney of diethylstilbestrol-treated male Syrian hamsters (Liehr *et al.*, 1989) the biological significance of the diethylstilbestrol-generated adducts has not been determined, and specific mutations generated by exposure to diethylstilbestrol have not been identified thus far.

(ii) In vitro

Diethylstilbestrol induces aneuploidy and DNA strand breaks in human cells *in vitro* (IARC, 1987a,b; Rupa *et al.*, 1997; Schuler *et al.*, 1998; Quick *et al.*, 2008). Data on in-vitro induction of sister chromatid exchange, chromosomal aberrations, and mutations in human cells were inconclusive (IARC, 1987a,b). More recent studies found additional evidence of diethylstilbestrol-induced sister chromatid exchange in cultured human lymphocytes, but at cytotoxic diethylstilbestrol concentrations (Lundgren *et al.*, 1988; Konac *et al.*, 2005). Data on induction of micronuclei by diethylstilbestrol remain equivocal (Fauth *et al.*, 2000; Clare *et al.*, 2006;), while studies on the induction of unscheduled DNA synthesis in human cells *in vitro* were mostly negative (IARC, 1987a,b). Diethylstilbestrol inhibited the polymerization of microtubules in human fibroblasts and prostate cancer cells, inducing metaphase arrest (Hartley-Asp *et al.*, 1985; Parry *et al.*,

1982), an effect that may underlie the induction of aneuploidy.

Diethylstilbestrol inhibited the in-vitro growth of human primary cervical cell strains, and inhibited colony formation at high concentrations (Johnstone *et al.*, 1984; Stanley *et al.*, 1985). Short-term exposure to diethylstilbestrol stimulated the growth of SV40-immortalized human endometrial stromal cells in soft agar, an effect that was inhibited by the anti-estrogen tamoxifen (Xu *et al.*, 1995). Chronic exposure of these cells to low concentrations of diethylstilbestrol markedly increased growth in soft agar (Siegfried *et al.*, 1984; Rinehart *et al.*, 1996). Thus, diethylstilbestrol caused the transformation of human endometrial stromal cells.

Repeated treatment with low doses of diethylstilbestrol of MCF-10F immortalized, non-tumorigenic, human epithelial breast cells increased colony formation in a soft agar assay at diethylstilbestrol concentrations ranging from 0.007–70 nM (Russo *et al.*, 2001, 2003). Growth of these cells in collagen changed from differentiated ductular growth to solid spherical masses with the same dose–response relationship. Invasive growth in a Boyden chamber assay was increased more than 10-fold at a diethylstilbestrol concentration of 70 nM (Russo *et al.* 2001, 2003). Different effects are seen with high doses of diethylstilbestrol. ER+ MCF-7 human breast cancer cells growth in soft agar was inhibited by diethylstilbestrol at concentrations of 2 μM and higher (Brandes & Hermonat, 1983).

Block *et al.* (2000) found effects of exposure to diethylstilbestrol in Ishikawa (endometrial carcinoma) cells, HeLa (cervical carcinoma) cells, and SKOV-3 (ovarian carcinoma) cells on mRNA expression of homeobox (HOX) genes that are involved in the development of the reproductive tract and other tissues.

Tests for in-vitro transformation in rat and Syrian hamster embryo cells gave positive results, while results in mouse cells were negative (IARC, 1987b). No mutations were found in BALB/C 3T3 cells transformed by diethylstilbestrol (Fitzgerald *et al.*, 1989).

Aneuploidy and DNA strand breaks were induced in rodent cells *in vitro* (IARC, 1987b), as confirmed in additional studies (Hayashi *et al.*, 1996; Tsutsui & Barrett, 1997; Tsutsui *et al.*, 1997). Results for chromosomal aberrations, micronuclei, and sister chromatid exchange were equivocal (IARC, 1987b), but in more recent studies, chromosomal aberrations, micronuclei, and sister chromatid exchange, as well as aneuploidy were found in a variety of rodent cell lines (de Stoppelaar *et al.*, 2000; Aardema *et al.*, 2006; Wakata *et al.*, 2006; Tayama *et al.*, 2008).

In a comparison of diethylstilbestrol-induced aneuploidy in human foreskin fibroblasts and Syrian Hamster embryo fibroblasts, the hamster cells appeared significantly more sensitive than the human cells (Tsutsui *et al.*, 1990).

The ability of diethylstilbestrol to bind covalently to tubulin in cell-free systems in the presence of an activating system (Sharp & Parry, 1985; Epe *et al.*, 1987), and to inhibit the polymerization of microtubules *in vitro* (Sharp & Parry, 1985; Sato *et al.*, 1987; Albertini *et al.*, 1993; Metzler & Pfeiffer, 1995), in Chinese hamster V79 cells and in Syrian hamster embryo cells (Tucker & Barrett, 1986; Sakakibara *et al.*, 1991; Ochi, 1999) may underlie the induction of aneuploidy. This microtubule-damaging property appears to be unique to diethylstilbestrol because it is not shared with estradiol or 17α-ethinyl estradiol, which are otherwise equally strong estrogens, and can be similarly genotoxic in some systems (Metzler & Pfeiffer, 1995).

Exposure to diethylstilbestrol did not induce mutations or unscheduled DNA synthesis (IARC, 1987b), except in a single study in Syrian hamster embryo cells, and in the presence of liver postmitochondrial supernatant from male rats pretreated with aroclor (Tsutsui *et al.*, 1984). Diethylstilbestrol did not inhibit intercellular communication and most studies did not find positive results for diethylstilbestrol in the mouse

lymphoma assay using L5178 $tk^{+/+}$ cells (IARC, 1987b; Sofuni *et al.*, 1996). Exposure of phage and plasmid DNA to diethylstilbestrol quinone resulted in a variety of mutations and, under certain conditions, recombinations in LacZ(α) following transfection into *E. coli* (Korah & Humayun, 1993).

Diethylstilbestrol did not induce mutation in a variety of bacterial and insect systems, but it was mutagenic in plants (IARC, 1987b). In assays with *Saccharomyces cervisiae* and other yeasts, diethylstilbestrol caused aneuploidy (IARC, 1987b), but it had mixed effects on induction of chromosomal losses (Albertini *et al.*, 1993), and, in most studies, it did not induce mutation, recombinations, or gene conversion (IARC, 1987b; Carls & Schiestl, 1994). DNA damage was not induced in fungi (yeasts) or bacteria, but diethylstilbestrol induced single-strand breaks in bacteriophage DNA in the presence of a horseradish peroxidase activation system (IARC, 1987b).

In vitro, rat liver and mammary gland mitochondria were able to oxidatively metabolize diethylstilbestrol to 4',4''-diethylstilbestrol quinone and to reduce diethylstilbestrol quinone to diethylstilbestrol (Thomas & Roy, 1995; Thomas *et al.*, 2004). Treatment of Syrian hamsters with diethylstilbestrol resulted in the formation of adducts in kidney mitochondrial DNA by [^{32}P]-postlabelling detected (Thomas & Roy, 2001a), and diethylstilbestrol treatment of rats induced similar adducts in liver mitochondrial DNA at higher levels than in nuclear DNA (Thomas & Roy, 2001b). In addition, both functional ERα and ERβ have been identified in mitochondria (Yager & Chen, 2007). Thus, mitochondria may be a target of diethylstilbestrol, and its mitochondrial effects conceivably play a role in its carcinogenic activity.

4.2.2 Indirect effects related to genotoxicity

(a) Cell proliferation and apoptosis

Diethylstilbestrol increased mitotic rate in Chinese hamster embryo cells, and in primary male hamster kidney tubular epithelial cells *in vitro* (Stopper *et al.*, 1994; Li *et al.*, 1995; Chen *et al.*, 1996). Chronic diethylstilbestrol treatment increased DNA synthesis in renal tubular cells isolated from male Syrian hamsters (Li *et al.*, 1993); this effect was blocked by co-treatment with a pure anti-estrogen (ICI 182780) (Chen *et al.*, 1996).

In-utero treatment of rats resulted in increased DNA synthesis in both the epithelium and stroma of the proximal portion of the Müllerian duct (which differentiate into oviduct) on the last day of gestation, but not in the caudal portion (which differentiate into upper vagina) where epithelial cell proliferation was actually depressed (Okada *et al.*, 2001). Neonatal exposure of mice to diethylstilbestrol resulted in markedly elevated DNA synthesis in epithelial, but not stromal cells of the vagina, whereas it increased the percentage of apoptotic stromal cells, but not epithelial cells at 90 days of age (Sato *et al.*, 2004). Following diethylstilbestrol treatment of pre-pubertal mice, DNA synthesis was markedly increased in the uterine and vaginal epithelium after 16–42 hours (Takahashi *et al.*, 1994). This effect was first apparent at 5 days of age and was still observed at 70 days (Suzuki *et al.*, 2006).

(b) Immune modulatory effects

There are several studies in mice that indicate some immune modulatory effects of diethylstilbestrol treatment. These appear to target the thymus, are highly dose-dependent, and differ in male and female animals (Calemine *et al.*, 2002; Utsuyama *et al.*, 2002; Brown *et al.*, 2006).

(c) Estrogen receptor-mediated effects

(i) Female animals

Diethylstilbestrol exposure *in utero* reduced the response of the mouse uterus weight and morphology to estrogenic stimulation by diethylstilbestrol on Days 22–25 of life, but not on Day 21 (Maier *et al.*, 1985). Neonatal diethylstilbestrol treatment reduced the responsiveness of uterus weight to ovariectomy, with or without subsequent estrogen stimulation in young adult mice (Medlock *et al.*, 1992), and reduced vaginal weight (Suzuki *et al.*, 1996).

The morphological appearance of the mammary glands of 2- to 11-month-old mice neonatally treated with diethylstilbestrol (0.1 µg daily for 5 days) was not different from that of untreated controls, but they developed hyperplasia more often in response to stimulation with estradiol. They showed the same response to stimulation with estradiol plus progesterone. The severity of the hyperplasia was increased in diethylstilbestrol-treated mice in response to both hormonal stimuli (Bern *et al.*, 1992).

Overexpression of ERα accelerated the onset of squamous metaplasia, atypical hyperplasia and adenocarcinoma of the uterus induced by neonatal diethylstilbestrol exposure by at least 4 months (Couse *et al.*, 1997). In αERKO mice, no uterine abnormalities, persistent vaginal cornification, or oviduct lesions were found following neonatal diethylstilbestrol treatment, and uterine weight was the same as in vehicle-treated αERKO mice (Couse *et al.*, 2001). This finding strongly suggests that the ERα is the mediator of the effects of neonatal diethylstilbestrol exposure in the female mouse genital tract (Couse & Korach, 2004). ERβ knockout mice (βERKO mice) had a normal morphological response to neonatal diethylstilbestrol treatment (Couse & Korach, 1999), related to the very low to absent expression of ERβ in the female mouse genital tract (Jefferson *et al.*, 2000).

In-utero diethylstilbestrol exposure caused persistent Müllerian duct structures resulting in a range of male and female genital tract abnormalities in mice, which are remarkably similar to those found in diethylstilbestrol-exposed humans (IARC, 1979a). Besides alterations in the uterus, cervix, and vagina, diethylstilbestrol also caused ovarian abnormalities in mice aged 3–14 months, exposed *in utero* (on Days 9–16 of gestation), and markedly increased ex-vivo ovarian production of progesterone, estradiol, and testosterone (Haney *et al.*, 1984).

(ii) Male animals

Neonatal diethylstilbestrol treatment of mice caused persistent decreases in weight of the male accessory sex glands at 12 months of age and the development of inflammation and dysplastic lesions in the posterior periurethral region of the accessory sex gland complex at 2, 12, and 18 months of age (Pylkkänen *et al.*, 1991b; 1993). After 12 and 18 months, there were also morphological changes in the testes (Pylkkänen *et al.*, 1991a; 1993). Treatment of these diethylstilbestrol-exposed mice at 2 months of age with estradiol caused squamous metaplasia in the periurethral prostatic ducts (Pylkkänen *et al.*, 1991b), and adult treatment with estradiol and 5*α*-dihydrotestosterone (via silastic implants) from 9–12 months of age exacerbated the inflammation and dysplasia at 12 months (Pylkkänen *et al.*, 1993). In contrast, prenatal diethylstilbestrol treatment did not have any lasting effects on the male accessory sex glands, except for occasional dysplasia in the ventral prostate lobe (Pylkkänen *et al.*, 1993). The prostatic weight decrease and lesion development were also found in mice exposed neonatally to diethylstilbestrol (Edery *et al.*, 1990). Neonatal exposure of rats to diethylstilbestrol enhanced the induction of prostatic dysplasia and cancer by subsequent chronic adult treatment with estradiol and testosterone (Yuen *et al.*, 2005). Diethylstilbestrol treatment of rats for 16 weeks with or without concomitant

testosterone treatment resulted in increased levels of lipid peroxidation products, and altered antioxidant activity in the ventral and dorsolateral prostate (Tam *et al.*, 2003).

Neonatal diethylstilbestrol treatment of male mice also resulted in decreased size of male accessory sex glands, particularly the seminal vesicles. Inflammation and dysplastic lesions developed in the glands of the ventral and dorsolateral prostate between 6–18 months of age and increased in severity with time (Prins *et al.*, 2001). When the same treatment was given to αERKO mice, no morphological effects were found after 6–18 months, whereas the neonatal diethylstilbestrol effects in βERKO mice were indistinguishable from those in wild-type mice (Prins *et al.*, 2001).

(d) Effects on gene expression (hormonal imprinting)

(i) Female animals

In-utero treatment with diethylstilbestrol caused changes in the expression of several genes, including the estrogen-responsive lactoferrin gene and the developmental *Hox* and *Wnt* genes, in the Müllerian duct/uterus of the developing murine fetus and of mice on the first days of life (Newbold *et al.*, 1997; Ma *et al.*, 1998; Miller *et al.*, 1998; Okada *et al.*, 2001).

The expression of a range of genes in the mouse uterus and/or vagina was permanently altered by neonatal exposure to diethylstilbestrol on the first 4–5 days of life up to postnatal Days 60–90, and included alterations in developmental *Hox* and *Wnt* genes (Miller *et al.*, 1998; Block *et al.*, 2000; Couse *et al.*, 2001; Li *et al.*, 2003a; Miyagawa *et al.*, 2004a, b; Sato *et al.*, 2004; Huang *et al.*, 2005; Newbold *et al.*, 2007; Tang *et al.*, 2008).

A single injection of diethylstilbestrol in prepubertal mice acutely altered the expression of genes coding for 3 TGFß isoforms in the uterus (Takahashi *et al.*, 1994). Treatment of young adult mice also altered the expression of several genes in the vagina and uterus (Klotz *et al.*, 2000; Miyagawa *et al.*, 2004a; Suzuki *et al.*, 2006).

The persistently increased expression of lactoferrin, c-*fos*, and *Nsbp1* in mice that were treated neonatally with diethylstilbestrol was associated with the persistent hypomethylation of CpG sequences in the promoter regions of these genes (Li *et al.*, 1997, 2003a; Tang *et al.*, 2008). Other mechanisms may also be involved in gene expression (Miyagawa *et al.*, 2004a, Tang *et al.*, 2008). The persistently decreased expression of *Hox* genes found in the uterus after 5 days of neonatal treatment with diethylstilbestrol (Couse *et al.*, 2001) was not associated with changes in methylation status of these genes (Li *et al.*, 2001). The decreased expression of most but not all developmental *Hox* and *Wnt* genes required the presence of ERα, because the expression of these genes is not affected when mice that lacked this estrogen receptor subtype are neonatally exposed to diethylstilbestrol (Couse *et al.*, 2001). The dose of diethylstilbestrol may be a major determinant of the size and direction of the effects on DNA methylation in the mouse uterus (Alworth *et al.*, 2002).

The mRNA expression of nucleosomal binding protein-1 (*Nsbp1*), which plays a role in chromatin remodelling, was permanently increased in mice treated neonatally with diethylstilbestrol for up to 18 months in a dose-related fashion (Tang *et al.*, 2008). A low-dose treatment resulted in a response in the expression and methylation pattern of the uterine *Nsbp*1 gene to the estrogen surge at puberty that was the opposite of that in control mice, but this phenomenon was dose-specific because a high diethylstilbestrol dose did not have this effect (Tang *et al.*, 2008). Ovarian hormones are important in the induction of uterine adenocarcinomas in mice treated neonatally with diethylstilbestrol, because prepubertally ovariectomized mice did not develop these tumours (Newbold *et al.*, 1990).

(ii) Male animals

Neonatal treatment with diethylstilbestrol of mice caused a persistent upregulation of the c-*fos* and c-*myc* proto-oncogenes in all male accessory sex glands (Pylkkänen *et al.*, 1993; Salo *et al.*, 1997), and a marked increase in the response of c-*fos* expression to estradiol injection at 3–5 months (Salo *et al.*, 1997). In 30-days-old F344 rats treated neonatally with diethylstilbestrol, the expression of both ERα and ERβ was increased as well as circulating prolactin (Khurana *et al.*, 2000). Neonatal treatment of mice caused changes in the expression of several other genes and in DNA methylation patterns (Sato *et al.*, 2006).

Neonatal exposure of mice to diethylstilbestrol resulted in a persistent reduction of androgen-receptor-protein expression in the ventral and dorsolateral prostate, ERβ expression was persistently decreased, and ERα expression (in stromal cells around prostatic ducts) was upregulated at postnatal Day 10 but not later in life (Prins *et al.*, 2001). This treatment also resulted in a persistent downregulation of a secretory protein, DLP_2, in the dorsolateral prostate. These effects of neonatal treatment with diethylstilbestrol were not seen in αERKO mice, whereas they were identical to those in wild-type mice in βERKO mice (Prins *et al.*, 2001).

4.3 Synthesis

Following exposure *in utero*, the oxidative metabolism of diethylstilbestrol can occur in fetal mouse tissues. There is some evidence that diethylstilbestrol binds covalently to DNA in fetal target tissue (uterus). In animal cells and tissues, diethylstilbestrol binds covalently to DNA and causes oxidative damage to DNA and lipids; some of these tissues are known targets of diethylstilbestrol-induced cancer in animals.

There is some evidence that diethylstilbestrol alters the expression of enzymes involved in diethylstilbestrol metabolism in rat.

Diethylstilbestrol causes aneuploidy in human and animal cells, most likely because of interference with microtubules, which requires oxidative metabolic activation. Diethylstilbestrol also induces chromosomal breaks and other chromosomal aberrations; this is likely to be a major mechanism of diethylstilbestrol-induced carcinogenicity.

Diethylstilbestrol can immortalize primary animal embryo cells *in vitro* and transform human breast cell lines. Diethylstilbestrol also increases the proliferation of human and animal cervical and uterine cells, and increases cell proliferation in diethylstilbestrol target tissues (uterus) in animals following neonatal and prepubertal exposure.

Neonatal exposure to diethylstilbestrol causes persistent changes in gene expression and DNA methylation patterns in diethylstilbestrol target tissues (prostate and uterus), and there is some evidence that hormone responsiveness is permanently altered in the mammary and prostate tissue of exposed mice.

Inflammatory and dysplastic prostate lesions are also observed in mice after neonatal exposure to diethylstilbestrol.

Several of the above effects of diethylstilbestrol, including mitogenic, gene expression, and prostatic effects, are mediated at least in large part by ERα.

There is some evidence of modulatory effects of perinatal exposure to diethylstilbestrol on the immune system in animals and humans.

It is likely that two or more of these factors in combination are responsible for the carcinogenic effects of diethylstilbestrol; estrogen receptor-mediated effects and genotoxicity conceivably both being involved, while other factors may be contributory. The early developmental changes in the female and male genital tract caused by exposure to diethylstilbestrol *in utero* or – in

rodents – neonatally, may result in epigenetic events that create a tissue and cellular environment conducive for the mechanisms responsible for the transplacental carcinogenic effects of diethylstilbestrol in humans and animals.

5. Evaluation

There is *sufficient evidence* in humans for the carcinogenicity of diethylstilbestrol. Diethylstilbestrol causes cancer of the breast in women who were exposed while pregnant. Diethylstilbestrol also causes clear cell adenocarcinoma in the vagina and cervix of women who were exposed *in utero*. Also, a positive association has been observed between exposure to diethylstilbestrol and cancer of the endometrium, and between in-utero exposure to diethylstilbestrol and squamous cell-carcinoma of the cervix, and cancer of the testis.

There is *sufficient evidence* in experimental animals for the carcinogenicity of diethylstilbestrol.

Overall evaluation

Diethylstilbestrol is *carcinogenic to humans (Group 1)*.

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