In ovo exposure of fish to the synthetic estrogen ethinyl estradiol can cause genetic males to sexually differentiate as phenotypic females (Papoulias et al. 1999). Presumably, the binding of estrogen to the estrogen receptor (ER) initiates the little-understood process of establishing the male phenotype in teleost fishes. Because many man-made chemicals bind to the ER, the question arises of whether environmentally exposed male fish are at risk of being feminized.

Although use of dichlorodiphenyltrichloroethane (DDT) and its metabolites dichlorodiphenyldichloroethylene (DDE) and dichlorodiphenyldichloroethane (DDD) continue to be found in fish tissues at concentrations of concern. Like o,p’-DDT, o,p’-DDE is estrogenic and is believed to exert its effects through binding to the estrogen receptor. The limited toxicologic data for o,p’-DDE suggest that it decreases fecundity and fertility of fishes. We conducted an egg injection study using the d-rR strain of medaka and environmentally relevant concentrations of o,p’-DDE to examine its effects on sexual differentiation and development. The gonads of exposed fish showed no evidence of sex reversal or intersex. However, other gonadal abnormalities occurred in exposed individuals. Females exhibited few vitellogenic oocytes and increased atresia. Male testes appeared morphologically normal but were very small. Gonadosomatic index values for both sexes were lower for exposed fish. Our observations of abnormal female and very small male gonads after in ovo o,p’-DDE exposure may be indicative of effects on early endocrine processes important for normal ovarian and testicular development. 

**Key words:** egg injection, medaka, o,p’-DDE, sexual development, sexual differentiation, xenooestrogen.

Materials and Methods

**Test organism.** The d-rR strain of medaka was a generous gift of Akihiro Shima (University of Tokyo, Tokyo, Japan). Broodstock were maintained at the Columbia Environmental Research Center (CERC) in well water under an 18:6 hr light:dark photoperiod at 27°C. In this strain, either R (orange-red) or r (white) is carried by the X or Y chromosome, respectively. White females (XrX) crossed with orange-red males (XYR) produce approximately equal numbers of white daughters and orange-red sons. Crossovers or genetic imbalances occur at a rate of about 0.005–0.5%, making coloration a reliable marker of genetic sex (Hishida 1965).

In addition to the genetic marker, there is distinct sexual dimorphism in medaka. Males bear a notched dorsal fin, an anal fin with a convex and serrated posterior margin, and an elongate penultimate anal fin ray that give their anal fins a square appearance. In addition, papillar processes form on the rays of the anal fin in breeding males. Females lack the dorsal notch, and their anal fins are more concave, smooth at the margin, and lack extended rays.

**Injection exposure. Preparation.** Details for embryo exposure and rearing are provided in Papoulias et al. (1999). Embryos were collected from breeding pairs of the d-rR strain of medaka, and egg injection was performed. The d-rR strain of medaka was a generous gift of Akihiro Shima (University of Tokyo, Tokyo, Japan). Broodstock were maintained at the Columbia Environmental Research Center (CERC) in well water under an 18:6 hr light:dark photoperiod at 27°C. In this strain, either R (orange-red) or r (white) is carried by the X or Y chromosome, respectively. White females (XrX) crossed with orange-red males (XYR) produce approximately equal numbers of white daughters and orange-red sons. Crossovers or genetic imbalances occur at a rate of about 0.005–0.5%, making coloration a reliable marker of genetic sex (Hishida 1965).

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in the morning of the day before exposure and embedded in a solid 1% agarose (Sigma Chemical Co., St. Louis, MO) matrix that had been set up in square 36-grid petri dishes (Falcon, Lincoln Park, NJ). The agarose matrix provided the necessary stability for injecting the embryos. The dish was then filled with well water and stored in a cool place (−20°C) until injection (within 24 hr).

**Injection.** Immediately preceding injection, dead embryos or embryos that had completed epiboly were replaced, and the well water covering the embryos was replaced with a sterile saline solution. Aluminosilicate capillary tubes (1.0 mm outer diameter and 0.53 internal diameter; Sutter Instrument Co., Novato, CA) were used to make injection needles with 5–10 µm internal-diameter tips. A calculated volume of material (~0.1% of egg volume; egg weight, 1.0 mg ± 0.2 mg/egg) was injected directly into the oil globule using a Narashigi picoinjector (PLI-188; Nikon, Inc., Melville, NY) and micromanipulator (MM-3; Stoelting Co., Wood Dale, IL). The injected embryos were left in the agarose at room temperature until the next day.

**Incubation.** Approximately 24 hr after injection, dead embryos were culled and recorded, and the survivors were placed in well water in 150-mL glass side-arm test tubes (Corning, Corning, NY) for incubation (rolled at 27°C by a gentle stream of air). Dead embryos were removed daily and counted.

**Grow-out.** Upon hatch, the medaka larvae were moved to 12.7 × 12.7 × 16.5 cm containers suspended in 137.2 × 35.6 × 30.5 cm stainless steel raceways supplied with a constant flow of well water (~300 mL/min). An 18:6 hr light:dark photoperiod and 25–27°C temperatures were maintained throughout rearing. Three times per day, the newly hatched fry were fed day-old brine shrimp (Artemia salina) and finely ground flake food (Wardley Spectra IV; Secaucus, NJ). After reaching 2 weeks of age, the medaka were provided 2-day-old brine shrimp and flake food. Feeding continued at three times daily during the week and once per day on weekends. The fish were moved to 12.7 × 15.2 × 22.9 cm stainless steel screen cages (200 mm² mesh) after 1–2 months and were maintained there until they reached maturity. Research was conducted in accordance with the CERC Animal Welfare Plan and approved by CERC’s Animal Care and Use Committee.

**Experimental design.** o,p′-DDE (99.8% pure; Chem Service, Westchester, PA) was dissolved in methylene chloride to the appropriate concentrations via serial dilution. After transfer to sterile triolein (95% pure, Sigma), the carrier of choice for these injections, the methylene chloride was removed by evaporation. Embryos (36 per treatment) were injected with a 0.5 nL volume of triolein alone (control) or one of three concentrations of o,p′-DDE (0.5, 0.05, 0.005 ng/embryo) in the carrier triolein. Adult fish were identified as genetic males (XY, orange-red) or genetic females (XX, white) at 107 days after fertilization and were measured (total length) and weighed (blotted dry) to assess growth. All were sacrificed in a concentrated solution of MS-222 (Sigma), and the gonads were dissected from a subsample of five white and five red fish to assess gonadosomatic index (GSI), sex reversal, and gonad histopathology. GSI was calculated as gonad weight divided by somatic weight × 100. Sex reversal was determined by comparing fish color (genetic sex) to the phenotypic sex as determined by inspection of the gonad. Histologic analysis of the preserved gonads (Bouin’s solution; Sigma) followed standard procedures for processing, dewaxing, hydration, and dehydration (Luna 1968). All sections were cut at 7 µm and stained using hematoxylin and eosin.

**Data analysis.** Mean body weight, body length, and GSI were tested for differences among control and o,p′-DDE-treated groups. Values for GSI ratios were arcsine transformed before analysis using one-way analysis of variance (ANOVA), testing males and females separately. We used a two-way ANOVA to test the interaction of sex and treatment on weight and length. A general linear model (α = 0.05) and least-squares means were used to detect any significant differences. The tests were performed using SAS software (SAS 2000).

### Results

**Survival and growth.** Survival was highest in the triolein-exposed fish (69%) and lowest in the 0.5 ng o,p′-DDE/embryo treatment (44%). Fish from the highest o,p′-DDE exposure (0.5 ng/embryo) were significantly larger than fish exposed to lower doses or the control (Table 1), and there was no significant interaction between treatment and color (genetic sex) on fish size.

**Gonadosomatic index.** GSI was inversely related to o,p′-DDE exposure for both males and females (Table 1). The lower GSI values for the exposed fish resulted from greatly decreased gonad weights.

**Secondary sexual characteristics.** Anal fin breeding tubercles or processes were observed on all triolein-injected males but on only one o,p′-DDE-injected individual (0.005 ng/embryo). No tubercles were observed on any of the embryos injected with 0.05 or 0.5 ng o,p′-DDE. All of the other secondary sexual characteristics (i.e., fin morphology) appeared appropriate for the sex phenotype.

**Gonadal histopathology.** Histologic examination of the gonads of the o,p′-DDE-exposed males and females indicated that no sex reversal or intersexes were caused by o,p′-DDE. However, female medaka exposed in ovo to o,p′-DDE did display gonadal abnormalities. All treated females possessed very few vitellogenic oocytes and exhibited an increased incidence of atresia, whereas untreated female gonads appeared mature, had empty follicles, and contained oocytes at various developmental stages (Figure 1A and B). The testes of both treated and untreated males were mature, but testes were markedly smaller in treated fish (Figure 1C and D).

### Discussion

Male-to-female sex reversal was not observed at any dose of o,p′-DDE (0.005–0.5 ng/egg) in our study. This differs from the results of Stewart et al. (2000), who did observe male-to-female sex reversal in d-rR medaka exposed in ovo to o,p′-DDE. This inconsistency may be due to the differences between the parent compound and the metabolite or, more likely, the concentration: in the experiments

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**Table 1.** Total length, weight, and GSI [mean ± SD (n)] of adult males and females exposed to different doses of o,p′-DDE in ovo.

| o,p′-DDE (ng/embryo) | Female Length (mm) | Male Length (mm) | Female Weight (g) | Male Weight (g) | Female GSI | Male GSI | Gonad weight Female | Male |
|----------------------|--------------------|-----------------|-------------------|---------------|-----------|---------|--------------------|------|
| 0                    | 26 ± 1             | 27 ± 2          | 0.16 ± 0.02       | 0.18 ± 0.03   | 3.12 ± 2.11| 0.58 ± 0.24| 0.0048 ± 0.003     | 0.001 ± 0.0006|
| 0.005                | 27 ± 1             | 27 ± 1          | 0.17 ± 0.03       | 0.18 ± 0.02   | 1.42 ± 0.21**| 0.09 ± 0.07**| 0.0028 ± 0.0006     | 0.0002 ± 0.0001|
| 0.05                 | 26 ± 1             | 27 ± 2          | 0.15 ± 0.02       | 0.17 ± 0.04   | ND        | 0.09 ± 0.06**| 0.002 ± 0.0001      | ND   |
| 0.5                  | 29 ± 1**           | 29 ± 1**        | 0.21 ± 0.03**     | 0.23 ± 0.04**| 0.87 ± 0.11**| 0.09 ± 0.04**| 0.0019 ± 0.0002     | 0.0002 ± 0.0001|

ND, no data available for gonad weights of females.

* Longer than triolein-injected controls and 0.05-exposed females (p < 0.05). ** Longer or heavier than triolein-injected controls and lower dose exposed males (p < 0.05). † Heavier than triolein-injected controls and lower dose exposed females. ‡ Lower GSI than triolein-injected controls (p < 0.05).
of Stewart et al. (2000), 227 ± 22 ng o,p'-
DDT/egg was required for sex reversal, an
exposure approximately 400 times our highest
concentration. Metcalfe et al. (2000) have
reported that maternal exposure to o,p'-DDT
(egg concentrations estimated at 80–102
ng/egg) failed to produce intersex progeny.
Although the lack of male offspring produced
by treated females might have been indicative
of complete feminization of genetic males,
these authors did not consider this finding
definitive evidence of sex reversal because their
experiments were not conducted with fish that
had a male genetic marker (e.g., d-rR strain).
Carlson et al. (2000) injected groups of
mixed-sex and monosex rainbow trout
(Oncorhynchus mykiss) and mixed-sex chinook
salmon (Oncorhynchus tschawytscha) embryos
with o,p'-DDE in ranges of 10–160 mg/kg
and 1–80 mg/kg, respectively. In their first set
of trout experiments, these authors observed
an elevated male:female sex ratio at 80 and
160 mg/kg and a single intersex individual at
the lethally toxic 160 mg/kg exposure. Their
subsequent experiments with trout and
salmon did not indicate an increase in males
over females, and no further evidence of inter-
sex was found. The lack of an effect on sexual
phenotype after in ovo o,p'-DDE exposure in
the experiments of Carlson et al. (2000) are
consistent with our results with medaka. However, whereas we observed a marked
effect on GSI, they reported none for the sub-
sample of females from the mixed-sex trout
experiment that were reared to maturity; male
GSI was not reported. Carlson et al. (2000)
concluded that o,p'-DDE-induced mortality
was likely to mask the more subtle effects on
sexual development.

The observed effects on gonadal develop-
ment and histopathology in the present study
are consistent with some previous studies of
effects of DDT exposure on fishes, yet inconsist-
sent with other studies. Female white croak-
ers (Genyonemus lineatus) embryos exposed
to 0.5 ng o,p'-DDE results may be questionable
because of differences in developmental stages
at which fish were exposed. Adult fathead
minnows (Pimephales promelas) males exposed
for 21 days to low concentrations of estrogen
and estrone showed complete inhibition of
testicular growth during recrudescence (Panter
et al. 1998). Exposing sexually mature male
and female fathead minnows to 17α-estradiol
for 14 days caused a reduction in male sec-
ondary sexual characteristic development and
degenerative testis changes, whereas ovarian
development appeared retarded and produced
more atretic oocytes than in unexposed
females (Miles-Richardson et al. 1999). It is
interesting to note that male summer flounder
(Paralichthys dentatus) exposed as juveniles to
o,p'-DDT displayed degenerative features
similar to those in adult fatheads exposed to
estrogen (Zaroogian et al. 2001), perhaps fur-
ther supporting the idea that exposure effects
will vary depending on the life stage at which
exposure occurs.

Estrogen exposure typically has the toxic
effect of repressing gonadal and somatic
growth; consequently, we do not consider that
the larger size of the fish in our highest o,p'
DDT treatment was due to anabolic effects of
the xenoestrogen (Donaldson et al. 1979;
Papoulias et al. 1999). Although we attempted
to feed our fish to excess, we cannot be certain
that the body size differences we saw were due
to an o,p'-DDE effect because of the lowered
survival of the highest treatment group.
Higher mortality resulted in lower tank den-
sity, potentially allowing more food per fish in
these treatments. Nevertheless, gonad weight
relative to somatic weight decreased with
increasing o,p'-DDT concentration. We sug-
uggest that exposure to nonlethal concentrations
of (xeno)estrogens early in development may
be analogous to chemical castration in mam-
mals, which diverts energetic resources nor-
mally used to develop mature gonads toward
somatic growth.

Our results indicate that male medaka
embryos exposed to ≤ 0.5 ng/embryo of
o,p'-DDE are not at risk of being feminized.
Although estrogens at this concentration can

Figure 1. Gonadal sections of female (A and B) and male (C and D) of adult d-rR medaka exposed in ovo to triolein solvent (A and C) and 0.5 ng o,p'-DDE/embryo (B and D).
caused sex reversal (Papoulias et al. 1999), the comparatively lower affinity of \( \alpha,\beta\)-DDE and \( \alpha,\beta\)-DDT for the ER (Nimrod and Benson 1997) suggests that higher exposures of these compounds are required for sex reversal to occur. Nevertheless, \( \alpha,\beta\)-DDT and \( \alpha,\beta\)-DDE at low concentrations may interfere with the binding of natural ligands to a variety of steroid binding moieties (e.g., receptors and binding proteins) (Danzo 1997; Donohoe and Curtis 1996; Gaido et al. 1997; Kupfer and Bulger 1976; Lundholm 1998; Mason and Schulte 1980; Nimrod and Benson 1997; Shilling and Williams 2000; Wells and Van Der Kraak 2000), thereby allowing for endocrine-disrupting effects.

Whether the effects on gonad development that we observed in the medaka fish result from disruption of the endocrine system specifically or are a consequence of other mechanisms of toxicity was not determined in the present study. Chemically induced genotoxic and nongenotoxic effects during development may manifest at early or later ontogenetic stages (McNabb et al. 1999).

Although our method of exposing the developing embryos through injection mimics maternal transfer of contaminants, it also allows for disruption of the development and differentiation of many tissues and processes specifically occurring during embryogenesis. Reproductive toxicity of the \( \alpha,\beta\)-DDE-exposed medaka in our study was evident by the small, underdeveloped gonads and suggests early impairment along the brain–pituitary–gonadal axis.

Few data are available regarding environmental concentrations of \( \alpha,\beta\)-DDE in eggs and embryos from which risks to fish populations can be assessed. Concentrations found in Lake Michigan salmonid eggs have been reported to range from 3 to 150 \( \mu \)g/kg (Giesy et al. 1986; Miller 1993). Data collected in the early 1990s from the northwestern United States indicate that fish tissue concentrations of 8–22 \( \mu \)g/kg may still be encountered (Brown 1997; Munn and Gruber 1997). At these \( \alpha,\beta\)-DDE concentrations, toxic effects were observed in our medaka.

We have shown that the reproductive development of both males and females may be impaired by maternally derived concentrations of \( \alpha,\beta\)-DDE as low as 0.005 ng/embryo (or 5 ng/g egg). Our observations of small but normal male testes and abnormal female ovaries after in \( \alpha,\beta\)-DDE exposure may be indicative of disruption of early endocrine processes that lead to normal ovarian and testicular development. Although \( \alpha,\beta\)-DDE body burdens are generally quite low (parts per billion), our data suggest that \( \alpha,\beta\)-DDE may affect sexual development but is unlikely to affect sexual differentiation in offspring of most exposed fishes.

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