Developmental exposure to a brominated flame retardant: An assessment of effects on physiology, growth, and reproduction in a songbird, the zebra finch

Margaret L. Eng [a,*], Tony D. Williams [a], John E. Elliott [b]

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[b] , , fi , , 4 3 2,

A R I C L E I N F O

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Mixtures of polybrominated diphenyl ethers (PBDEs) have been widely used as additive flame retardants, and BDE-99 is one of the most predominant congeners found in the environment. BDE-99 has been reported in avian samples worldwide, yet knowledge of its toxicity to birds is minimal. We assessed the short- and long-term effects of nestling exposure to environmentally relevant levels of BDE-99 in a model passerine, the zebra finch. Early exposure to BDE-99 did not affect hematocrit, oxidative stress, or thyroid hormones in either the juvenile or adult stages, and there were no effects on chick growth or survival. BDE-99 exposure caused a dose-dependent delay in timing of reproduction, but there were no other effects on reproductive success. In zebra finches, endpoints related to reproductive behavior appear to be the most sensitive to BDE-99. However, passerines overall appear to be less sensitive than birds of prey or mammals to PBDE exposure.

1. Introduction

Polybrominated diphenyl ethers (PBDEs) are a group of hydrophobic and bioaccumulative chemicals that find commercial use as flame retardants, and have become ubiquitous in environmental, human, and wildlife samples (Hites, 2004). 2,2′,4,4′,5-Pentabromodiphenyl ether (BDE-99) is one of the most pervasive congeners (Hites, 2004). In mammals, dosing with BDE-99 has been shown to cause a wide range of adverse effects, including disruption of thyroid hormone homeostasis (Hakk et al., 2002; Kuriyama et al., 2007), oxidative stress (Albina et al., 2010; Belles et al., 2010), and interference in reproductive development and behavior (Talsness et al., 2005; Lilienthal et al., 2006).

BDE-99 is consistently found in avian tissue and egg samples throughout the world (Chen and Hale, 2010; Morrissey et al., 2010), yet its effects in birds are not well known due to a lack of pertinent toxicological literature. There have been some avian exposure studies using penta-BDE mixtures, but these show considerable variation in the sensitivity of bird species to PBDEs. American kestrels ( ) exposed during development to a penta-BDE mixture containing 27.2% BDE-99 were reported to exhibit some mild effects on growth (Fernie et al., 2006), thyroid hormones and oxidative stress (Fernie et al., 2005), and kestrels exposed in

exposure may not be evident until the individual reaches reproductive maturity, necessitating long-term studies to assess fitness implications of early, developmental exposure to contaminants. Here, we investigate the long-term effects of early developmental exposure to environmentally relevant levels of BDE-99 in birds, using the zebra finch ( ) as a model passerine species. The zebra finch is a useful model to monitor effects of

tissue residue data was 14079.69 ng/g lw. Control birds had detectable levels of BDE-99, however lipid normalized concentrations of BDE-99 in control birds were approximately 2.5× lower than the lowest dose group, and 42× lower than the highest dose group. The safflower control oil had no detectable PBDEs, so the BDE-99 in control birds was either due to possible cross-contamination between treatment groups within the nest, or background levels of BDE-99.

There was no effect of BDE-99 dose on day 30 ($_{4,95}$ = 0.63, = 0.645) or adult ($_{4,95}$ = 1.06, = 0.383) hematocrit levels (Table 1), and there was no effect of sex on day 30 ($_{1,90}$ = 0.96, = 0.330) or adult ($_{1,90}$ = 0.19, = 0.663) hematocrit levels.

On day 30 there was no effect of BDE-99 dose on TAC ($_{4,51}$ = 0.61, = 0.655), TOS ($_{4,51}$ = 0.93, = 0.456) or OSI ($_{4,46}$ = 1.04, = 0.399; Table 1). Similarly in adults, there was no effect of dose on TAC ($_{4,70}$ = 1.21, = 0.312), TOS ($_{4,83}$ = 0.88, =

approximately 3 days in the 50.7 ng/g bw/day dose group, and about 6 days in the 173.8 ng/g bw/day dose group compared to the control group.

4. Discussion

In this study we assessed the long-term effects of early developmental exposure to the polybrominated diphenyl ether congener BDE-99 on selected physiological variables, growth, and reproduction in zebra finches. As previously demonstrated through tissue residue analysis (Eng et al., 2012), our doses resulted in plasma and adipose burdens that fall within the range of concentrations reported in free-living birds (e.g. Lindberg et al., 2004; McKinney et al., 2006; Voorspoels et al., 2007). At these ecologically-relevant dose concentrations, there were no effects on a range of endpoints including hematocrit, oxidative stress, thyroid hormone homeostasis, chick growth and survival. There was also no effect on female reproductive success in adults, although there was evidence that females exposed to higher concentrations of BDE-99 during early development were more likely to delay onset of egg laying. Overall we observed very few effects in 30-day-old or adult birds following early developmental exposure to BDE-99, similar to the results of a study of PBDE exposure in European starlings, which concluded that passerine species may be relatively less sensitive to the effects of PBDEs (Van den Steen et al., 2010).

It has been suggested that hematocrit can be used as an indicator of whether a pollutant has caused changes in the red blood cell volume or number (Handy and Depledge, 1999). In the present study, 30-day and adult hematocrit levels were unaffected by nestling exposure to BDE-99. Other studies that have looked at the effect of BDE-99 or penta-BDE exposure in birds also found no effect on hematocrit (Murvoll et al., 2005; Van den Steen et al., 2010; Winter et al., 2013). In contrast, there is some evidence in mammals that PBDE exposure has hematological effects. In free living harbor seals ( ) the red blood cell count was inversely related to ΣPBDEs in the blood (Neale et al., 2005), and in ranch mink ( ) hematocrit decreased following exposure to a commercial PBDE mixture (Martin et al., 2007). However, at least in the mink study the dose groups that showed an effect had tissue PBDE concentrations approximately three orders of magnitude higher than in our study (18,505 μg/g lw and 27,909 μg/g lw versus up to 14079.69 ng/g lw in the present study). Alternatively, it is possible that the red blood cells in birds may be less sensitive to PBDE exposure than in mammals, as the hematological cells differ

BDE-99 and its hydroxylated (OH) metabolites are structurally similar to thyroid hormones, and have the potential to disrupt thyroid hormone homeostasis through various mechanisms, such as competitive displacement of thyroid hormones from thyroid hormone transport proteins (Ucan-Marin et al., 2009). There is evidence in mammals that BDE-99 can alter T4 concentrations (Hakk et al., 2002;

related chemicals that examine additional reproductive endpoints such as sex steroid hormone concentrations, histology of the reproductive tract, and female mating behavior could be informative for understanding effects on avian reproduction.

In conclusion, early developmental exposure to BDE-99 at concentrations relevant to free-living birds had very few long-term negative effects in zebra finches. Similarly, a study in European starlings concluded passerines were less sensitive than other bird species to PBDE exposure (Van den Steen et al., 2010). Another possibility for the lack of observed effects in our study may be that while our doses covered a range of concentrations comparable to those reported in free-living birds, higher concentrations or mixtures of PBDE congeners may be needed to cause more overt adverse effects. Alternatively, the embryonic life stage may be more sensitive than the nestling period, and exposure may be necessary to see effects on physiology and reproduction. Future studies looking at higher concentrations and timing of exposure would be needed to confirm this. We did observe negative effects on laying behavior in female zebra fi

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