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High feather mercury concentrations in the wandering albatross are related to sex, breeding status and trophic ecology with no demographic consequences

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ABSTRACT

Hg can affect physiology of seabirds and ultimately their demography, particularly if they are top consumers. In the present study, body feathers of >200 wandering albatrosses from Possession Island in the Crozet archipelago were used to explore the potential demographic effects of the long-term exposure to Hg on an apex predator. Variations of Hg with sex, age class, foraging habitat (inferred from $\delta^{13}C$ values), and feeding habits (inferred from $\delta^{15}N$ values) were examined as well as the influence of Hg on current breeding output, long-term fecundity and survival. Wandering albatrosses displayed among the highest Hg feather concentrations reported for seabirds, ranging from 5.9 to 95 $\mu g\ g^{-1}$, as a consequence of their high trophic position ($\delta^{15}N$ values). These concentrations fall within the same range of those of other wandering albatross populations from subantarctic sites, suggesting that this species has similar exposure to Hg all around the Southern Ocean. In both immature and adult albatrosses, females had higher Hg concentrations than males (28 vs. 20 $\mu g\ g^{-1}$ dw on average, respectively), probably as a consequence of females foraging at lower latitudes than males ($\delta^{13}C$ values). Hg concentrations were higher in immature than in adult birds, and they remained fairly constant across a wide range of ages in adults. Such high levels in immature individuals question (i) the frequency of moult in young birds, (ii) the efficiency of Hg detoxification processes in immatures compared to adults, and (iii) importantly the potential detrimental effects of Hg in early life. Despite very high Hg concentrations in their feathers, neither effects on adults' breeding probability, hatching failure and fledgling failure, nor on adults' survival rate were detected, suggesting that long-term bioaccumulated Hg was not under a chemical form leading to deleterious effects on reproductive parameters in adult individuals.

1. Introduction

Mercury (Hg) is a non-essential element that bioaccumulates in organisms and biomagnifies through food webs. Both processes are due to the conversion of inorganic Hg into organic forms (mainly methylmercury, MeHg) in aquatic ecosystems, MeHg being highly bioavailable and toxic. As such, MeHg is harmful to biota, being associated with adverse effects such as neurological, immunological, physiological and reproductive impacts in both humans and wildlife (e.g., Evans et al., 1982; Thompson and Furness, 1989a; Burger and Gochfeld, 1997; Tan et al., 2009). Nonetheless, the natural occurrence of Hg (Nriagu, 1996) has involved adaptations of predators to the presence of this toxic metal in their environment. This is particularly obvious for many top predators whose high trophic position and long life span lead to important levels of exposure. Most marine top predators feed on fish and cephalopods, which concentrate Hg mainly under MeHg (Bloom 1992; Bustamante et al., 2006). Marine apex predators have thus developed efficient detoxification capacities to support elevated exposure to MeHg (reviews in Cuvin-Aralar and Furness, 1991; Das et al., 2000). In marine mammals, demethylation of MeHg in the liver leads to the production of non-toxic granules of tiemannite (Koeman et al., 1973; Martoja and Berry, 1980). The accumulation of tiemannite granules makes the liver the ultimate organ of retention of Hg (Wagemann et al., 1998, 2000). Since

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these granules are not excreted (Nigro and Leonzio, 1996), inorganic Hg is basically stored through the whole life, thus inducing particularly elevated and increasing liver Hg concentrations throughout life, without any apparent toxic effect (Cuvin-Aralar and Furness, 1991).

In aquatic birds, efficiency of Hg detoxification processes is critical to prevent the toxic effects of Hg, which can affect their breeding, hatching and fledging successes (Tan et al., 2009; Frederick and Jayasena, 2010; Tartu et al., 2013; Goutte et al., 2014a, 2014b). As in mammals, demethylation of Hg in the liver appears to be a significant detoxification mechanism in seabirds (Thompson and Furness, 1989b; Thompson et al., 1993). However, birds present another complementary and efficient way to detoxify and excrete Hg on a regular basis, namely moult. Hg binds to keratin in the form of MeHg, hence, most feather Hg is MeHg (Thompson and Furness, 1989a), thus leading to a direct elimination of the toxic organic form during feather growth and subsequent loss. Feathers are considered as the main route for Hg excretion in seabirds (Monteiro and Furness, 1995), with feather growth contributing to the elimination of $>90\%$ of the Hg accumulated since the previous moult (Braune and Gaskin, 1987). In some cases, moult of all feathers is synchronous, as in penguins that renew their whole plumage in a few weeks (Brasso et al., 2013; Carravieri et al., 2013, 2014a), but generally moult is sequential and takes many weeks to months to be completed. For example, the wandering albatross *Diomedea exulans* replaces its feathers slowly and infrequently over several consecutive inter-breeding periods (Weimerskirch, 1991) and this extreme moulting pattern is believed to contribute significantly to high feather Hg concentrations in the species (Anderson et al., 2009; Becker et al., 2002).

The present study adds new information on Hg exposure, the factors explaining its variations, and its demographic consequences on the wandering albatross breeding at Possession Island in the Crozet archipelago (southern Indian Ocean). There, an exceptional long-term demographic capture-mark-recapture survey (1965-present) allows a robust knowledge of the life history of each individual (Weimerskirch et al., 1997). The wandering albatross was chosen as a model animal because (i) it is an apex predator that occupies the highest trophic position within the diverse community of subantarctic seabirds, being thus submitted to contaminant biomagnification processes (Blévin et al., 2013), (ii) it is a very long-lived species (>50 years) making it a species of particular interest to investigate Hg bioaccumulation patterns over the long term (Tavares et al., 2013; Carravieri et al., 2014b), and (iii) consequently the species presents consistently high Hg levels in various tissues, including liver, blood and feathers (Hindell et al., 1999; Stewart et al., 1999; Anderson et al., 2009; Carravieri et al., 2014b, 2014c). The study is a companion work to a broader investigation using the same birds and data set that focused on (i) the complex foraging pattern of wandering albatrosses according to age, sex and breeding status using stable isotopes (Jaeger et al., 2014), (ii) the effect of all these factors and foraging ecology as explanatory variables of blood contaminants (Hg and persistent organic pollutants) (Carravieri et al., 2014b), and (iii) the corresponding consequences of blood contamination levels on birds' demography (Goutte et al., 2014b).

We focused here on Hg in body feathers to complement the previous investigations on blood, because the two tissues represent short- and long-term exposure to Hg, respectively. Blood Hg is directly influenced by recent dietary intake, while feathers are representative of Hg bioaccumulation over the inter-moult period (at least two years for body feathers in the wandering albatross). Our goal was three fold, by increasing order of importance (i) to describe body feather Hg concentrations in a larger data set of sampled birds ($n>200$) than in most previous investigations on marine predators, (ii) to quantify the main intrinsic (sex, age and breeding status) and extrinsic (foraging habitat and trophic position) factors contributing to Hg variation, and (iii) the demographic consequences of feather Hg levels in terms of current probabilities of breeding success, and of long-term apparent probabilities of adult survival, return to the breeding colony, and breeding, hatching and fledgling successes. We also further investigated the surprising recent finding on a few birds showing that feather Hg concentrations were higher in young immature wandering albatrosses than in older immatures and adults (Tavares et al., 2013).

2. Materials and methods

2.1. Study area, species and fieldwork

Wandering albatrosses nest on subantarctic islands throughout the Southern Ocean. The study was conducted at Possession Island in the Crozet Archipelago (46°S, 52°E), Southern Indian Ocean, where 300–400 pairs nest each year (Delord et al., 2008). Although the minimal age at first reproduction is five years old, ten years is the mean age of first breeding in this population (Weimerskirch et al., 1997). Wandering albatrosses return to their breeding grounds each year in December and females lay a single egg in late December–early January. Both parents incubate alternatively until hatching in March. Chicks are reared for ≈ 280 days and most young are fledged in November. It was recently demonstrated that up to 6% of the birds that fledged a chick still breed 2 years in a row, and the species is now considered as a quasi-biennial breeding species (Barbraud and Weimerskirch, 2012). Approximately 80% of birds that failed the previous year engage in another breeding attempt the following year. All wandering albatrosses had been ringed and sexed as part of a long-term mark recapture programme (Weimerskirch et al., 1997), with nestlings being ringed since 1965. In December, prebreeding adults are counted over the whole island. From mid-January to mid-February, nest contents were checked every ten days to determine the identity of the breeding pairs and breeding status (egg laid/egg hatched) of each individual. In mid-April, June and August, all nests are checked to monitor the survival of chicks.

In the present work, sampled wandering albatrosses were grouped per sex according to their breeding history and age: (i) immatures refer to young birds (3–11 years) that never bred, and (ii) adult albatrosses were those that bred at least once. From 21 December 2007 to 04 March 2008, body feathers were collected on 201 immature and adult wandering albatrosses. Since Hg is mostly excreted in growing feathers, Hg level in feathers is considered to be a reliable measure of Hg bioaccumulation since the last moult (Furness et al., 1986). In wandering albatrosses, feather replacement takes place exclusively during the non-breeding period (Weimerskirch, 1991). Once collected, body feathers were stored dry in individual plastic bags.

2.2. Hg and stable isotope analyses

Four body feathers per individual were pooled to obtain a mean isotopic value and an average of Hg level for body feathers (Bond and Diamond, 2008; Jaeger et al., 2014; Carravieri et al., 2014a). Prior to chemical analysis, feathers were cleaned to remove surface contaminants using a 2:1 chloroform:methanol solution followed by two successive methanol rinses. After cleaning, body feathers were oven dried for 48 h at 50 °C. Total Hg was measured at the laboratory Littoral Environnement et Sociétés (LIENSs) with an Advanced Mercury Analyzer