Behavioral hypothermia of a domesticated lizard under treatment of the hypometabolic agent 3-iodothyronamine

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Abstract: Ectothermic animals rely on behavioral thermoregulation due to low capacity of heat production and storage. Previously, lizards were shown to achieve ‘fever’ during microbial infection by increasing their preferred body temperature (PBT) behaviorally, thereby attaining a relatively high survival rate. The purpose of this study was to investigate whether domesticated lizards pursued ‘behavioral hypothermia’ induced by a hypometabolic agent 3-iodothyronamine (T1AM). We found that treatment with 8.0 mg/kg T1AM caused a lizard species, the leopard gecko (Eublepharis macularius), to decrease its ventilation and oxygen consumption rates 0.64- and 0.76-fold, respectively, compared to those of the control (P<0.05). The lizards, habituated at an ambient temperature of 30 ± 0.5°C, also showed a significant decrease in the PBT range over a freely accessible thermal gradient between 5°C and 45°C. The upper limit of the PBT in the treated lizards lowered from 31.9°C to 30.6°C, and the lower limit from 29.5°C to 26.3°C (P<0.001). These findings demonstrate that the treated lizards pursued behavioral hypothermia in conjunction with hypoventilation and hypometabolism. Because prior studies reported a similar hypometabolic response in T1AM-injected laboratory mice, the domesticated lizards, as a part of the vertebrate phylogeny, may be a useful laboratory model for biological and pharmacological researches such as drug potency test.

Key words: 3-iodothyronamine, behavioral hypothermia, lizards, metabolism, thermoregulation

Introduction

The regulation of body temperature (Tb) is crucial for animals to maintain homeostasis to ensure optimal function and a high probability of survival [5, 7, 17]. Although a large difference exists in physiological thermoregulatory capacity (e.g., heat generation and storage) between ectothermic and endothermic vertebrates, the principal mechanism of thermoregulation appears to be shared in the vertebrate phylogeny [2, 17, 19]. Fever and hypothermia are special physiological mechanisms for survival in critical conditions such as those resulting from microbial infection or external stressors [4, 16]. The two mechanisms may thus provide a good opportunity to examine the hypothesis that the basis of thermoregulation is conserved in the vertebrates. A representative example is seen in fever, a form of hyperthermia produced by the endogenous pyrogens of the host in response to bacterial endotoxins. An important finding is that the desert iguana (Dipsosaurus dorsalis) induced fever after bacterial infection by raising their preferred body temperature (PBT) behaviorally, leading to an
increase in survival rate [18]. By analogy with behavioral fever in lizards, we may ask whether ectotherms voluntarily induce ‘behavioral hypothermia’ in accordance with a well-defined hypometabolic state (see below).

Previous reports have shown that hypometabolism and hypothermia can be induced in non-hibernator rodents by administration of brain extracts from hibernating animals [15] or of certain chemicals, such as 3-iodothyronamine (T1AM) and H2S [1, 14]. For instance, mice treated with a single dose of T1AM reduced their metabolic rate until Tb decreased to \( \sim 30^\circ C \) over the first 90 ~ 120 min of exposure [11]. Normothermia was then gradually restored 4 to 6 h after injection. Another comparable example is seen in the administration of H2S to mice. Interestingly, the same substance (in the form of Na2S) also produced hypometabolic and hypoventilatory effects in a fish, the blue cod (Parapercis colias) [6]. In the fish study, however, because the water (thus body) temperature was maintained at a constant value, it is not known whether the individuals would voluntarily reduce Tb to produce a hypometabolic response.

In the current study, we injected T1AM into the leopard gecko (Eublepharis macularius) to investigate whether the chemical affects the metabolic and thermoregulatory activity of this organism. T1AM is known to be naturally produced by the enzymatic deiodination and decarboxylation of thyroid hormone T4 [13]. T1AM has been found to trigger a hypometabolic response of target cells via a specific transmembrane receptor such as G-protein-coupled receptor (e.g., trace amine-associated receptor 1, TAAR1) [14]. As deiodinase, decarboxylase and TAARs are found in most vertebrates [8–10], it is presumed that the interaction of T1AM with the receptor is conserved in the vertebrates. We therefore tested the hypothesis that the T1AM-treated lizards induce hypothermia behaviorally over a freely exploitable thermal gradient. The results of this study may fill the gap in the current knowledge of the fundamental thermoregulatory mechanism of the ectotherms. The results will also give an opportunity to examine whether the domesticated reptiles can be used as a laboratory model for biological and pharmacological researches. These issues have been overlooked to date.

### Material and Methods

#### Animals

This study was carried out in accordance with the Guide for the Animal Care and Use of the Committee on the Ethics of Animal Experiments of Yonsei University Wonju Campus. The protocol was approved by the Committee on the Ethics of Animal Experiments of Yonsei University (Permit Number: YWC-130115-2). Leopard geckos (E. macularius; 18.9 ± 2.1 g, n=26, 1 year old) were purchased from a local supplier. Before the experiments, all the subjects were habituated for a week under a light:dark cycle of 12:12 h with lights on 07:00, a relative humidity of \( \sim 40\% \) and a cage temperature of 30 ± 0.5°C maintained with a heating pad under one side of the cage. The animals were fed daily with a diet of gut-loaded mealworms supplied at night. All the experiments were conducted after 19:00 as these geckos are nocturnal.

#### Ventilation rate

To determine an appropriate dose of T1AM, the ventilation rate (VR, counts per min) was first tested at four different doses injected intraperitoneally (i.p.) in 2 − 3 subjects per group: 0 mg/kg (vehicle control), 4 mg/kg, 8 mg/kg and 16 mg/kg. Each of the doses was dissolved in 60% dimethyl sulfoxide (DMSO) and 40% saline (pH 7.4) [14]. The VR was measured by counting the number of thoracic movements every 10 min for the first hour and subsequently every 30 min until the end of the experiment. The dose of 8 mg/kg T1AM was chosen as an appropriate one because the subjects did not further decrease the VR at 16 versus 8 mg/kg (see below in the Results), and because prior observations showed that rodent subjects often died at relatively high doses during experiments, possibly due to a prolonged bradycardia [14]. Once the protocol was decided, the VR was determined with six to eight lizards by injecting the vehicle or T1AM.

#### Oxygen consumption rate

The general procedure for measurements of oxygen consumption rate (VO2) was described in our previous reports [11, 12]. The six lizards were fasted for 24 h before the experiment. An individual subject was placed in a 340-ml metabolic chamber set at 30 ± 0.5°C. The subject was stabilized for 1 h in the chamber and was injected i.p. with either DMSO or T1AM (8 mg kg\(^{-1}\)).
The VO₂ data were collected every 10 min with an Oxy-
max System (Columbus Instruments, Columbus, OH, 
USA) that included an automated, open-circuit equal-
flow system connected to the metabolic chamber. The 
incident air supplied to the chamber was set at 550 
ml/min. Excurrent air subsamples were collected at 500 
ml/min, diverted through desiccant columns and sent to 
the O₂ sensor. The gas analyzer signals were transmitted 
to a personal computer. The VO₂ was calculated accord-
ing to a Hill’s equation, expressed as a mass-specific 
value and corrected to standard temperature (0°C) and 
pressure (760 Torr).

Preferred body temperature
The PBT of the lizards was measured over a thermal 
gradient between 5°C and 45°C set up on a copper plate 
(W × L × T=70 mm × 905 mm × 5 mm). This plate was 
surrounded by 170-mm high acrylic plates to isolate the 
subjects from the external environment. To generate the 
thermal gradient, one end of the copper plate was warmed 
by a controlled heat block and the other end cooled by a 
circulator containing an anti-freeze mixture. After the set-
ing was completed, the Tₜ of each lizard was monitored 

Fig. 1. Representative records of ventilation rates of leopard geckos treated with only DMSO 
(vehicle control) (A) or T1AM at dosages (mg/kg) 4.0 (B), 8.0 (C) and 16.0 (D). Data of 
the time period from 180 to 300 min were used for the statistical analysis (indicated in C 
with a gray bar on the x-axis).

Statistical analysis
The data are presented as mean ± SD. The significance 
of differences in VR between groups was tested via in-
dependent samples t-tests. Differences in VO₂ and PBT 
between treatments were assessed via paired-samples 
t-tests. The procedure was performed with SPSS/PC+, 
and significance was accepted at the level of P<0.05.

Results
The VR of the control animals stabilized at a level of 
13 to 17 CPM within 30 min of DMSO injection (Fig. 
1). The VR decreased slightly further at a dose of 4 
mg/kg T1AM, but decreased considerably to 4 ~ 10
counts/min at 8 mg/kg. After 400 min post-injection, the VR at these doses returned to a value at or above the control level. The VR remained at 5 ~ 9 counts/min for up to 930 min at a dose of 16 mg/kg T1aM (Fig. 1D). From these results, we chose a dose of 8 mg/kg as a suitable dosage of T1aM and a 2-h time frame from 180 min to 300 min for the subsequent analyses.

Table 1. Summary data for ventilation rate, oxygen consumption rate and upper and lower limits of preferred body temperature in leopard gecko

<table>
<thead>
<tr>
<th>Variables</th>
<th>Control2</th>
<th>T1AM2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventilation rate (counts/min)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average VR*</td>
<td>11.6 ± 1.9</td>
<td>7.4 ± 1.6</td>
</tr>
<tr>
<td>1Minimum VR*</td>
<td>8.9 ± 2.1</td>
<td>3.0 ± 2.8</td>
</tr>
<tr>
<td>(n = 6)</td>
<td>(n = 8)</td>
<td></td>
</tr>
<tr>
<td>Oxygen consumption rate† (ml/g/h)</td>
<td>0.075 ± 0.011</td>
<td>0.056 ± 0.014</td>
</tr>
<tr>
<td>(n = 6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preferred body temperature (°C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper limit (UL)‡</td>
<td>31.9 ± 0.5</td>
<td>30.6 ± 1.7</td>
</tr>
<tr>
<td>Lower limit (LL)‡</td>
<td>29.5 ± 1.3</td>
<td>26.3 ± 1.1</td>
</tr>
<tr>
<td>(n = 6)</td>
<td></td>
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</table>

Data: mean ± SD. 1Minimum VR is the mean of the single lowest VRs of individual subjects over 180 to 300 min post-injection. 2Significance of differences between DMSO and T1AM treatments: *, \( P<0.001 \) (independent t-test); †, \( P=0.03 \) (paired t-test); ‡, \( P<0.001 \) (paired t-test).

![Fig. 2. Typical records of oxygen consumption rates (VO₂) for a gecko injected with vehicle (A) or T1AM (B). Note that the subject in either treatment showed relatively stable levels of VO₂ for 180 to 300 min (indicated with gray bars) that were averaged and used as a representative value for that measurement.](image)

The VO₂ was determined using six subjects treated with and without T1AM (Fig. 2). The average VO₂ was 0.072 when the animals were treated with only the vehicle, but it decreased 0.76-fold for the same animals injected with T1AM (paired t-test, \( P=0.03 \)) (Table 1).

Figure 3 illustrates the experimental apparatus with a gecko on a copper plate that displayed a thermal gradient between 5°C and 45°C (A to C). Figures 3D and 3E presents typical \( T_b \) readings over ~400 min post-injection for two animals, each with and without T1AM treatment. The \( T_b \) profile was nearly identical in both conditions for up to 180 min post-injection. The \( T_b \) values subsequently diverged, with the subjects treated with T1AM showing lower \( T_b \) ranges. With the T1AM treatment, the average upper limit (UL) of the PBT decreased from 31.9°C to 30.6°C, and the lower limit (LL) decreased from 29.5°C to 26.3°C (paired t-test for both UL and LL, \( P<0.001 \)) (Table 1).
Discussion

Ectotherms respond to thermoregulatory demands primarily by behavioral means. These demands are adaptive since the optimal $T_b$ causes increases in reproductive, digestive and performance capacity [7, 20]. The behavioral mode of response is observed even in the special case of fever in the lizard *D. dorsalis*. In this situation, the PBT range shifted to a higher level in the presence of a bacterial infection, resulting in a higher survival rate [18]. Thus, in light of the fundamental principle of thermoregulation, we investigated whether ec-
totherms show the ability to attain hypothermia behaviorally.

We found that T1AM was effective for inducing hypoventilation and hypometabolism in the geckos. The average VR and VO2 were reduced 0.64- to 0.76-fold as a result of T1AM treatment (Table 1). These results suggest that the reptiles might have the same cellular mechanism to that of rodents for interaction of T1aM with its membrane receptors which then trigger hypometabolism. It is worth noting that the quantity of T1aM required for the induction of hypometabolism in lizards was 1/6.25 of the quantity required in mice (8 vs. 50 mg/kg) [14]. This difference may partly reflect the low VO2 of the lizards compared to mice (0.072 vs. 1.93 ml/g/h) at the standard or normal Tb [11].

Our final goal was to investigate whether the T1AM-induced hypometabolism was accompanied by behavioral hypothermia. The results of the experiment supported our hypothesis. The experiment furnished the first evidence that both the upper and lower limits of the PBT in lizards treated with T1AM were significantly lower than those of the same animals treated with only the vehicle DMSO. Because the subjects were free to move along the thermal gradient, it appeared that hypothermia was pursued behaviorally under the T1AM-induced hypometabolic state. This differential change in the PBT occurred at 150 to 180 min post-injection, the time at which T1AM was fully effective for hypoventilation and hypometabolism (Figs. 1 and 2). Conversely, our results may imply that the lizards exploit a relatively low thermal environment and remain in a low Tb range, as do mammalian hibernators, when reduction of metabolic rate is crucial for survival (e.g., during times of food shortage) [2, 3].

In conclusion, the T1AM-treated lizards voluntarily pursued behavioral hypothermia. This result is consistent with hypoventilation and hypometabolism. Although the adaptive significance of hypothermia was not directly explored in this study, a reduction of energy expenditure, with decreased VR and VO2, would be beneficial to ectotherms in certain conditions like food shortage. Our result provides valuable evidence that the principal thermoregulatory mechanism might be conserved in the same phylogenetic lineage including the domesticated reptiles as well as laboratory mice.

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