Adrenocorticotropic hormone and corticosterone responses to acute hypoxia in the neonatal rat: effects of body temperature maintenance

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Bruder ED, Kamer KJ, Guenther MA, Raff H. Adrenocorticotropic hormone and corticosterone responses to acute hypoxia in the neonatal rat: effects of body temperature maintenance. Am J Physiol Regul Integr Comp Physiol 300: R708–R715, 2011. First published December 29, 2010; doi:10.1152/ajpregu.00708.2010.—The corticosterone response to acute hypoxia in neonatal rats develops in the 1st wk of life, with a shift from ACTH independence to ACTH dependence. Acute hypoxia also leads to hypothermia, which may be protective. There is little information about the endocrine effects of body temperature maintenance during periods of neonatal hypoxia. We hypothesized that prevention of hypothermia during neonatal hypoxia would augment the adrenocortical stress response. Rat pups separated from their dams were studied at postnatal days 2 and 8 (PD2 and PD8). In one group of pups, body temperature was allowed to spontaneously decrease during a 30-min prehypoxia period. Pups were then exposed to 8% O2 for 3 h and allowed to become spontaneously hypothermic or externally warmed (via servo-controlled heat) to maintain isothermia. In another group, external warming was used to maintain isothermia during the prehypoxia period, and then hypoxia with or without isothermia was applied. Plasma ACTH and corticosterone and mRNA expression of genes for upstream proteins involved in the steroidogenic pathway were measured. Maintenance of isothermia during the prehypoxia period increased baseline plasma ACTH at both ages. Hypothermic hypoxia caused an increase in plasma corticosterone; this response was augmented by isothermia at PD2, when the response was ACTH-independent, and at PD8, when the response was ACTH-dependent. In PD8 rats, isothermia also augmented the plasma ACTH response to hypoxia. We conclude that maintenance of isothermia augments the adrenocortical response to acute hypoxia in the neonate. Prevention of hypothermia may increase the stress response during neonatal hypoxia, becoming more pronounced with increased age.

PERIODS OF ACUTE HYPOXIA are among the more common neonatal stresses, particularly with prematurity (11, 21–23). Neonatal hypoxia can become a devastating condition requiring mechanical ventilation, O2 therapy, corticosteroids, and other supplemental therapies (29, 42, 43). Coordinated physiological and metabolic responses to hypoxia and a complete understanding of the development of these responses are crucial for positive clinical outcomes (13, 14, 25, 27).

Neonatal hypoxia leads to spontaneous hypothermia in a variety of mammalian species and may have the salutary effect of decreasing total body O2 consumption and metabolism (6, 12, 26, 45). To our knowledge, there are no specific guidelines for the control of body temperature in infants during periods of acute hypoxia. The consensus appears to be that prevention of hypothermia during hypoxia is warranted, even though this may place an additional neural and metabolic stress on the infant. Conversely, the use of therapeutic hypothermia following periods of neonatal hypoxia to minimize hypoxic-ischemic encephalopathy has received much attention, as it has been shown to decrease brain injury during reoxygenation (16, 28, 39).

We previously demonstrated that the neonatal corticosterone response to acute hypoxia shifts from relative ACTH independence to ACTH dependence between postnatal day 2 (PD2) and postnatal day 8 (PD8) (4). We also documented a profound spontaneous decrease in body temperature during acute hypoxia. This phenomenon has been termed the “hypoxic thermal response” and is thought to protect an organism from severe metabolic stress and brain damage by allowing a decrease in whole body O2 consumption (33, 40).

The current study evaluated the ACTH and corticosterone responses to acute hypoxia in PD2 and PD8 rats. We assessed responses in pups allowed to become spontaneously hypothermic compared with those in which hypothermia was prevented by maintenance of body temperature. Assuming that the hypothermic response to hypoxia is a beneficial adaptation, as has been suggested previously (26), we hypothesized that preventing the decrease in body temperature would constitute an additional stress to the animal. Therefore, we hypothesized that aggressive maintenance of isothermia would augment pituitary-adrenocortical responses to acute hypoxia in the neonatal rat.

METHODS

Animal treatment and experimental protocol. The Aurora Health Care Institutional Animal Care and Use Committee approved the animal protocol. Timed-pregnant Sprague-Dawley rats at gestational day 15 or 18 (n = 117) were obtained from Harlan Sprague Dawley (Indianapolis, IN) and maintained on a standard diet and water ad libitum in a controlled environment (lights-on from 0600 to 1800, 23°C room temperature). The size of litters born in-house was normalized (12–14 rats/litter, mixed sexes). On the morning of experimentation, litters without dams were placed in an environmental chamber. Pups were placed on a standard heating pad (Moore Medical, Farmington, CT) overlaid with an adequate amount of bedding. Litters were kept separate during the experiment, with each litter occupying a ~6 × 12 in. space in the chamber. For the first 30 min (prehypoxia period), 21% O2 was supplied to the chamber at a rate of ~8 l/min, and rectal temperature was recorded in one sentinel pup per litter using RET-3-Iso probes and a BAT-12 digital thermometer connected to a SBT-5 switchbox (Physitemp Instruments, Clifton, NJ). The base of the temperature probe was taped to the pup’s tail to keep the probe in place. Pups were allowed to huddle together at the beginning of the experiment, with care taken to keep the sentinel pup within the huddle. All pups were allowed to move freely once experimentation was commenced.

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Group I: prehypoxia body temperature not controlled. Body temperature was allowed to decrease during the prehypoxia period (i.e., thermoneutrality was not maintained). After the prehypoxia period, the O2 concentration of the chamber was decreased to 8% for 3 h. Body temperature was allowed to spontaneously decrease (hypoxia-hypothermia) or was maintained using servo-controlled external heat (hypoxia-isothermia). Servo-controlled heat entailed small adjustments to the heating pad setting in response to changes in body temperature. In the hypoxia-isothermia group, the target body temperature was set at the level at the end of the prehypoxia period. A separate set of litters was exposed to 21% O2 for 3 h, and their body temperature was not controlled (normoxia; time-control).

Group II: prehypoxia body temperature controlled. Thermoneutrality was maintained during the prehypoxia period using servo-controlled heat, as described above. Again, a separate set of litters was exposed to 21% O2 for 3 h, but body temperature was maintained using servo-controlled external heat (normoxia-isothermia). During the hypoxic exposure, body temperature was manipulated as follows: 1) spontaneous decrease (hypoxia-hypothermia; no external heat), 2) spontaneous decrease, but with constant external heat set at the level required to maintain isothermia in normoxic pups (hypoxia-hypothermia; low external heat), or 3) isothermia maintained using servo-controlled external heat (hypoxia-isothermia). For all rats in group II, the target body temperature was defined as the value obtained at the onset of the prehypoxia period.

Sample collection. Baseline measurements were obtained following the 30-min prehypoxia period, at which time half of each litter was removed from the chamber and killed. Trunk blood was pooled and collected in EDTA, and adrenal glands were pooled and quickly frozen in liquid nitrogen (2–3 rats per plasma or adrenal sample). After 3 h at 8% or 21% O2, the remaining pups were removed from the chamber and killed, and samples were collected as they were at baseline.

Hormone assays. Plasma ACTH and corticosterone were measured by radioimmunoassay, as described previously (MP Biomedicals, Solon, OH) (31).

RNA isolation and real-time PCR analysis. Real-time PCR was performed on total RNA isolated from adrenal glands using the RNaseasy Mini protocol (Qiagen, Valencia, CA). The concentration of RNA was quantified using a Qubit fluorometer (Invitrogen, Carlsbad, CA). All RNA samples were diluted to a final concentration of 10–20 ng/μL in the PCR assay. The Taqman One-Step RT-PCR protocol and premade primers and probes (Applied Biosystems, Foster City, CA) were used for all real-time assays. The final reaction volume of 25 μL consisted of 1× AmpliTaq Gold DNA polymerase mix, 1× RT enzyme mix containing MultiScribe reverse transcriptase and RNase inhibitor, 1× primer/probe mix, and 50–100 ng of total RNA. The following thermal cycle conditions were used during amplification and detection performed with the ABI Prism 7900HT Sequence Detection System: 48°C for 30 min reverse transcription, 95°C for 10 min, and 40 cycles at 95°C for 0.25 min and 60°C for 1 min. Each sample was assayed in triplicate. The number of cycles required to reach a predetermined threshold value in the intensity of the PCR signal [cycle threshold (Ct) value] was used to quantify gene expression.

Statistical analyses. Hormone and real-time PCR data were analyzed by two-way ANOVA. Body temperature data were analyzed by two-way ANOVA for repeated measures; P < 0.05 was considered significant. All post hoc analyses were performed by Student-Newman-Keuls method for multiple comparisons (SigmaStat 2.03).

RESULTS

Initial body temperature (obtained immediately upon instrumentation) at the start of the 30-min prehypoxia period was 32.6 ± 0.3°C in PD2 rats and 34.4 ± 0.3°C in PD8 rats (P < 0.001). Values at both ages were similar to those previously reported for pups allowed to huddle in the absence of the dam (1, 10). Changes in body temperature during the 30-min prehypoxia (control) period are shown in Fig. 1A. Body temperature in group I pups (no external heat) significantly decreased at both ages during the prehypoxia period (F1,51 = 82.4, P < 0.001). Use of servo-controlled heat during the prehypoxia period (group II) maintained body temperature near isothermia at both ages. Application of external heat to maintain body temperature (group II) during the prehypoxia period elicited a significant increase in plasma ACTH at both ages (Fig. 1B)

Fig. 1. Changes in body temperature during prehypoxia period (A) and baseline (end of 30-min prehypoxia period) ACTH (B) and corticosterone (C) concentrations. Values are from group I (nonthermoneutral) and group II (thermoneutral) pups at postnatal days 2 and 8 (PD2 and PD8); n = 11–16 for body temperature measurements, and n = 13–35 for baseline ACTH and corticosterone measurements. *Significantly different from initial body temperature or from group I within the same age group (P < 0.05). +Significantly different from PD2 within the same experimental group (P < 0.05).

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compared with ACTH in group I pups at the same age ($F_{1,82} = 26.2, P < 0.001$). In addition, the ACTH response was more pronounced in group II PD8 than group II PD2 pups ($F_{1,82} = 9.9, P = 0.002$). There was no significant effect of body temperature maintenance during the prehypoxia period on plasma corticosterone (Fig. 1C), while plasma corticosterone was significantly lower in PD8 pups, regardless of the strategy used to maintain body temperature ($F_{1,83} = 22.8, P < 0.001$). Baseline ACTH and corticosterone values were similar to those previously reported by us in pups maintained with their lactating dams (31).

Figure 2 shows changes in body temperature during 3 h of normoxia (time control) in group I and II pups at both ages. In PD2 pups exposed to normoxia without application of external heat (heat off), body temperature decreased significantly and progressively between each time point ($P < 0.002$), except between 90 and 120 min ($P = 0.345$). PD8 pups exposed to normoxia for 3 h (heat off) did not exhibit significant changes in body temperature between time points; however, body temperature decreased significantly by the end of the 3-h period compared with baseline (0.8°C; $P = 0.019$). While there were fluctuations in body temperature in PD2 pups exposed to normoxia for 3 h (servo-controlled heat), changes were not significant. PD8 pups from the servo-controlled group exhibited a small decrease in body temperature between 0 and 30 min ($P < 0.001$), but body temperature was subsequently unchanged throughout the remainder of the 3-h period.

Table 1 lists plasma ACTH and corticosterone concentrations in group I and II pups following 3 h of normoxia. In group I PD2 pups (heat off), plasma ACTH and corticosterone were significantly increased following 3 h of normoxia ($P = 0.017$ and $P < 0.001$, respectively). Preventing the decrease in body temperature (Fig. 2) in normoxic PD2 pups with servo-controlled heat (group II) also prevented the increase in ACTH and corticosterone. In fact, plasma corticosterone in group II PD2 pups had decreased to below baseline levels following 3 h of normoxia ($P = 0.017$). The 3-h normoxic period had no significant effect on plasma ACTH or corticosterone in PD8 pups without (group I) or with (group II) maintenance of body temperature with external heat. Thus any effect of 3 h of maternal separation on ACTH and corticosterone was absent in PD8 pups.

Figure 3 displays changes in body temperature during 3 h of hypoxia in group I pups. Hypoxia (heat off) resulted in a significant decrease in body temperature after 30 min of exposure in PD2 ($F_{3,18} = 18.0, P < 0.001$) and PD8 ($F_{3,15} = 11.0, P < 0.001$) pups, and body temperature continued to decrease during most of the 3-h time period. The magnitude of the decrease in body temperature was greater in PD8 than PD2 pups after 2 h of hypoxia ($F_{1,11} = 5.8, P = 0.034$). Servo-controlled heat successfully maintained isothermia during acute hypoxia (albeit at the lower baseline levels shown in Fig. 1), as there were no significant changes in body temperature in PD2 or PD8 pups.

Plasma ACTH and corticosterone concentrations in group I PD2 and PD8 pups are shown in Fig. 4. In PD2 pups, hypoxia (heat off) did not affect plasma ACTH compared with normoxic values, and plasma ACTH was also not affected by hypoxia with servo-controlled heat. Hypoxia (heat off) in PD8

**Table 1. ACTH and corticosterone concentrations following 3 h of normoxia (21% O2): time control**

<table>
<thead>
<tr>
<th></th>
<th>ACTH, pg/ml</th>
<th>Corticosterone, ng/ml</th>
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<tbody>
<tr>
<td></td>
<td>Baseline</td>
<td>Normoxia</td>
</tr>
<tr>
<td></td>
<td>Baseline</td>
<td>Normoxia</td>
</tr>
<tr>
<td>Group I (no heat)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PD2</td>
<td>59 ± 2</td>
<td>104 ± 6*</td>
</tr>
<tr>
<td>PD8</td>
<td>69 ± 4</td>
<td>86 ± 4</td>
</tr>
<tr>
<td>Group II (servo-controlled heat)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PD2</td>
<td>86 ± 8</td>
<td>85 ± 7</td>
</tr>
<tr>
<td>PD8</td>
<td>117 ± 4</td>
<td>98 ± 3</td>
</tr>
</tbody>
</table>

Values are means ± SE; $n = 21−35$ (baseline) and 8–9 (normoxia). Thermoneutrality was not maintained during prehypoxia period in group I pups; nor was external heat applied during 3-h experimental period; the opposite was true in group II pups. Baseline represents values obtained after 30-min period preceding 3-h normoxic exposure. PD2 and PD8, postnatal days 2 and 8. *Significantly different from baseline within the specified age group ($P < 0.02$).

![Fig. 2. Changes in body temperature during 3 h of normoxia (21% O2; time control) in group I and II pups. Values are from group I and II pups at PD2 and PD8; n = 3–5 measurements per group (PD2 and PD8). +Significant decrease in body temperature from the previous time point within the specified age group ($P < 0.05$).](http://ajpregu.physiology.org/)

![Fig. 3. Changes in body temperature during 3 h of hypoxia in group I pups. External heat was not used during the prehypoxia period; therefore, pups were not thermoneutral at baseline. Values represent 6–8 measurements per experimental treatment at each age. *Significant decrease from the previous time point within the specified age group ($P < 0.05$). +Significant difference in the magnitude of reduction compared with PD2 at the specified time point (hypothermia only; $P < 0.05$).](http://ajpregu.physiology.org/)
Table 2. Adrenal real-time PCR in group I pups

<table>
<thead>
<tr>
<th>Gene</th>
<th>PD2 Baseline</th>
<th>Hypoxia (no external heat)</th>
<th>Isothermia (servo-controlled heat)</th>
<th>PD8 Baseline</th>
<th>Hypoxia (no external heat)</th>
<th>Isothermia (servo-controlled heat)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Star</td>
<td>18.50 ± 0.11</td>
<td>18.71 ± 0.09</td>
<td>18.96 ± 0.32</td>
<td>22.62 ± 0.17</td>
<td>22.23 ± 0.25</td>
<td>21.16 ± 0.11*</td>
</tr>
<tr>
<td>Ldr</td>
<td>28.50 ± 0.32</td>
<td>28.14 ± 0.57</td>
<td>26.58 ± 0.20</td>
<td>32.47 ± 0.39</td>
<td>31.09 ± 0.17*</td>
<td>30.62 ± 0.12*</td>
</tr>
<tr>
<td>Mc2r</td>
<td>24.29 ± 0.19</td>
<td>24.57 ± 0.07</td>
<td>25.26 ± 0.15*</td>
<td>30.02 ± 0.22</td>
<td>30.70 ± 0.10</td>
<td>29.84 ± 0.31</td>
</tr>
</tbody>
</table>

Values are means ± SE, expressed as number of cycles required to reach a predetermined threshold value (Ct); n = 4 pooled adrenal samples per experimental group at each age. A decrease in Ct indicates increased mRNA expression. Thermoneutrality was not maintained during prehypoxia period in group I pups. Baseline represents values obtained after 30-min prehypoxia period and immediately preceding hypoxic exposure. Litters were stratified into treatments during 3 h of hypoxia (8% O2). Star, steroidogenic acute regulatory protein; Ldr, LDL receptor; Mc2r, melanocortin 2/ACTH receptor. *Significantly different from baseline within the specified age group (P < 0.05).
The present study evaluated body temperature, ACTH, and corticosterone responses to acute hypoxia in PD2 and PD8 rats. We assessed differences in these responses between pups allowed to become spontaneously hypothermic and those in which hypothermia was prevented by control of external heat. We also examined the effects of these treatments on expression of adrenal Star, Ldlr, and Mc2r mRNA, genes that encode upstream proteins involved in the steroidogenic pathway. Hypoxia alone (no external heat) decreased body temperatures by ~10°C in pups at both ages. Hypoxia with spontaneous hypothermia increased plasma corticosterone at both ages, although plasma ACTH was increased in PD8 pups only. Maintenance of isothermia during hypoxia via servo-controlled external heat more than tripled the corticosterone response in PD2 rats and nearly doubled the corticosterone response in PD8 rats. Star and Ldlr mRNA expression was increased in PD8 adrenals when these pups were maintained at isothermia during the hypoxic exposure.

Baseline plasma ACTH and corticosterone values in the present studies were similar to those of pups maintained with their dams (31), indicating that the pups were not stressed by 30 min of maternal separation (prehypoxia period). We previously showed that a 4-h period of maternal separation under normoxic conditions does not effect body temperature, ACTH, or corticosterone in PD8 pups (4). Data from the present study confirm these findings, as 3 h of normoxia had no effect on plasma ACTH or corticosterone at PD8. In contrast, 3 h of normoxia in PD2 pups elicited a decrease in body temperature and increases in plasma ACTH and corticosterone. Maintenance of body temperature with servo-controlled external heat prevented these increases, indicating that decreased body temperature elicited the ACTH and corticosterone responses, and not maternal separation per se. Interestingly, maintaining thermoneutrality with servo-controlled external heat during the 30-min prehypoxic period resulted in a small increase in plasma ACTH at both ages.
Hypoxia with hypothymia was a significant physiological stressor and increased plasma corticosterone in PD2 and PD8 rats, as we showed previously (4). The present data clearly demonstrate that aggressive maintenance of body temperature amplifies the corticosterone response to acute hypoxtia, regardless of age. The data also indicate that the major stimulus for the corticosterone response at PD2 was not increased plasma ACTH concentration, whereas this was the case in PD8 rats. The lower basal plasma corticosterone concentration in PD8 pups was likely due to decreased adrenal sensitivity to ACTH and decreased levels of corticosteroid-binding globulin (2, 7).

What mechanisms defined these age-dependent shifts in hypothalamus-pituitary-adrenal (HPA) activity during acute hypoxtia? When body temperature in PD2 pups was not con- trolled during the prehypoxtia period (group I), subsequent hypoxtia with hypothymia increased plasma corticosterone without concomitant increases in ACTH. Maintenance of isothermia during hypoxtia increased plasma corticosterone further, with only a relatively minor increase in ACTH. In contrast, in pups that were thermoneutral during the prehypoxtia period (group II), this minor increase in ACTH did not occur. It is possible that increased corticosterone production during hypoxtia in PD2 pups was partially driven by postganglionic sympathetic nerve input into the adrenal cortex (32). It is also likely that increased steroid production was at least partially driven by direct activation of chromaffin cells (41). Chromaffin cells from PD2 rats can synthesize and secrete catecholamines in direct response to stressful stimuli, such as hypoxtia (37, 38). A local increase in catecholamine concentration might act in a paracrine fashion to stimulate steroid production, particularly since chromaffin cells are dispersed in the neonatal adrenal cortex (9, 36). This suggests that the corticosterone response to acute hypoxtia at PD2 was not the result of increased plasma ACTH.

If the corticosterone response during acute hypoxtia at PD2 was ACTH-independent, then the response at PD8 was likely to be ACTH-dependent. The dynamics of the ACTH and corticosterone responses at PD8 were similar to responses to acute stress in the adult rat. The ACTH responses observed in PD8 rats were, in turn, highly dependent on body temperature. As noted above, maintenance of isothermia during the prehypoxtia period increased plasma ACTH at baseline. This effect had a significant influence on temperature-dependent changes in ACTH during hypoxtia. Pups that were thermoneutral at baseline (group II) had more pronounced ACTH responses to hypoxtia with low external heat and to hypoxtia with isothermia than the same pups in group I (not thermoneutral at baseline). Hypoxia with hypothymia (no external heat) elicited similar ACTH responses in group I and II pups at PD8. Regardless of baseline body temperature, maintenance of isothermia during hypoxtia augmented plasma ACTH compared with pups treated with minimal external heat. This finding suggests a positive correlation between ACTH responses and aggressive mainte- nance of body temperature during hypoxtia in PD8 rats.

Corticosterone responses to acute hypoxtia in PD8 rats correlated with increased plasma ACTH levels, regardless of body temperature. A period of adrenocortical hyporesponsiveness to stimulation in the neonatal rat has been established, and PD8 occurs during the middle of this period (2, 44). The existence of such a period has been proposed as a protective mechanism to keep the rapidly developing brain from increased glucocorticoid exposure (35). Acute hypoxtia with spontaneous hypoxtmia overrode this hyporesponsiveness, and maintenance of isothermia further activated the HPA axis. Increased plasma ACTH in PD8 pups likely had a stimulatory effect on the expression of adrenal Star and Ldlr mRNA expression, which in turn could contribute to increased corticosterone production (3). Increases in plasma corticosterone at PD8 may also have been facilitated by direct stimulation of the adrenal cortex via the splanchnic nerves, as we previously showed that postganglionic sympathetic blockade can inhibit corticosterone responses to chronic neonatal hypoxtia (32). Furthermore, it is possible that neuronal stimulation of chromaffin cell catecholamine synthesis also played a role, and increased plasma epinephrine concentrations at PD8 would support this (15, 34).

Aggressive maintenance of isothermia without resolution of hypoxtia may expose the neonate to pathologically high glucocorticoid levels (18, 19). Blockade of corticosterone synthesis with metyrapone prevents hypoxtia/ischemia-induced losses in hippocampal function that occur 1 day after hypoxtia exposure (20). In addition, recent data suggest that the release of cortisol from corticosteroid-binding globulin is temperature-

Table 3. Adrenal real-time PCR in group II pups

<table>
<thead>
<tr>
<th>Gene</th>
<th>Baseline</th>
<th>Normoxia (servo-controlled heat)</th>
<th>Hypoxia</th>
<th>Isothermia (servo-controlled heat)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PD2</td>
<td>Low external heat</td>
<td>No external heat</td>
<td>PD2</td>
</tr>
<tr>
<td>Star</td>
<td>19.80 ± 0.17</td>
<td>20.90 ± 0.16*</td>
<td>19.62 ± 0.26†</td>
<td>19.29 ± 0.28†</td>
</tr>
<tr>
<td>Ldlr</td>
<td>26.92 ± 0.21</td>
<td>27.96 ± 0.26*</td>
<td>26.85 ± 0.35</td>
<td>26.15 ± 0.40‡</td>
</tr>
<tr>
<td>Mc2r</td>
<td>27.03 ± 0.25</td>
<td>27.44 ± 0.08</td>
<td>27.16 ± 0.19</td>
<td>27.46 ± 0.18</td>
</tr>
<tr>
<td></td>
<td>PD8</td>
<td></td>
<td></td>
<td>PD2</td>
</tr>
<tr>
<td>Star</td>
<td>18.34 ± 0.26</td>
<td>17.13 ± 0.37*</td>
<td>17.79 ± 0.11</td>
<td>17.21 ± 0.18*</td>
</tr>
<tr>
<td>Ldlr</td>
<td>24.30 ± 0.19</td>
<td>23.70 ± 0.71</td>
<td>22.71 ± 0.14*</td>
<td>23.44 ± 0.42*</td>
</tr>
<tr>
<td>Mc2r</td>
<td>26.15 ± 0.22</td>
<td>25.68 ± 0.20</td>
<td>26.53 ± 0.12†</td>
<td>26.33 ± 0.14</td>
</tr>
</tbody>
</table>

Values are means ± SE, expressed as number of cycles required to reach a predetermined threshold value (Ct); n = 4 pooled adrenal samples per experimental group at each age. Decrease in Ct indicates increased mRNA expression. Thermoneutrality was maintained during prehypoxtia period in group II pups. *Significantly different from baseline within the specified age group (P < 0.05). †Significantly different from normoxia within the specified age group (P < 0.05).
sensitive (5). Maintenance of isothermia during hypoxia may significantly augment the concentration of free (unbound) glucocorticoid, thereby amplifying the effects of increased adrenal cortical steroid production and, possibly, worsening the clinical outcome. Studies of the long-term consequences of glucocorticoid exposure (endogenous or exogenous) during the neonatal period have provided evidence of lasting defects in physiological function (8, 17, 30). On the other hand, generation of an augmented corticosterone response could be beneficial during neonatal hypoxia, if it resulted in improved pulmonary function (24).

What might be the central nervous system mechanism resulting in augmentation of the HPA response to hypoxia when isothermia was maintained? It is generally accepted that the hypoxic thermal response, also called hypoxia-induced anaplerxia, is due to a direct hypothalamic effect on the set point for body temperature (40). Isothermic hypoxia may have resulted in a discrepancy between core temperature and this set point, resulting in increased hypothalamic drive to the adrenal cortex. This could have occurred through efficient sympathetically activated nervous system pathways in PD2 pups or through corticotropin-releasing hormone neurons in the paraventricular nucleus, leading to large increases in plasma ACTH in PD8 pups.

Perspectives and Significance

We have provided evidence that maintenance of isothermia during an episode of acute hypoxia in the neonate should be reconsidered. Therapeutic interventions aimed at maintaining body temperature during correction of the O2 deficit may prevent a beneficial hypometabolic survival response (45). The increased metabolic stress placed on a hypoxic neonate maintained at isothermia may have significant short- and long-term consequences. We suggest that studies be undertaken to develop a consensus on the proper approach to the control of body temperature and possible untoward effects on pituitary-adrenocortical stress responses in the hypoxic infant.

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DISCLOSURES

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REFERENCES


