RESPIRATION DURING CHRONIC HYPOXIA AND HYPEROXIA IN LARVAL AND ADULT BULLFROGS (RANA CATESBEIANA)

II. CHANGES IN RESPIRATORY PROPERTIES OF WHOLE BLOOD

BY ALAN PINDER AND WARREN BURGGREN

Department of Zoology, University of Massachusetts, Amherst, MA 01003-0027, U.S.A.

(Received 2 August 1982—Accepted 2 March 1983)

SUMMARY

Rana catesbeiana Shaw tadpoles and adults were maintained at 20–23 °C under aerial and aquatic normoxia (P02 150 mmHg), hyperoxia (P02 275 mmHg) and hypoxia (P02 75 mmHg) for 4 weeks, after which the following blood measurements were made: haematocrit, red blood cell count, haemoglobin concentration, mean corpuscular haemoglobin concentration, O2 capacity, O2 equilibrium curve, Bohr shift, Hill's coefficient and intraerythrocytic concentration of nucleotide triphosphates (ATP+GTP) and 2,3-DPG.

Normoxic tadpoles had much higher blood O2 affinity (P50 9–10 mmHg) than adults (P50 35 mmHg) but a lower haemoglobin concentration, haematocrit and O2 capacity. The concentration of intraerythrocytic phosphates was higher in normoxic tadpoles than in adults, indicating that the higher O2 affinity of normoxic tadpole blood was due to the haemoglobins themselves, rather than affinity modulators.

Chronic hypoxia in tadpoles produced little change in whole blood P50, and no significant change in any other blood variable. In adult bullfrogs, on the other hand, O2 capacity doubled through polycythaemia, and the P50 decreased by 11 mmHg (35%), though apparently not from any significant change in concentration of intraerythrocytic phosphates. Hyperoxia produced no haematological changes in either larvae or adults.

In adult bullfrogs exposed to chronic hypoxia, the morphology of the gas exchange organs does not change (Burggren & Mwalukomo, 1983), but instead profound adjustments occur in the blood, favouring O2 transport under these conditions. The blood of the tadpole shows little or no response to chronic hypoxia, with morphological adjustments in skin, gills and lungs constituting the major response.

INTRODUCTION

Vertebrates experiencing environmental hypoxia generally respond initially by increasing convection of blood and air or water through the gas exchange organs, in order to maintain oxygen uptake. Since the energetic cost of increased cardiac output...

Key words: Acclimation, hypoxia, hyperoxia.
and ventilation is high, prolonged hypoxia may result in morphological changes of the
gas exchange organs (McDonald & McMahon, 1977; Lechner & Banchero, 1980;
Burggren & Mwalukomo, 1983) and/or changes in the respiratory properties of blood
(see Wood, 1980 for review).

The morphological consequences of chronic hypoxia and hyperoxia in larval and
adult bullfrogs are reported in the preceding paper (Burggren & Mwalukomo, 1983).
In the tadpole, a marked branchial hypertrophy, an increase in capillary mesh density;
and a decrease in the gas diffusion distance between blood and water in the skin, all
accompany chronic hypoxia. However, adult bullfrogs exposed to the same hypoxic
conditions showed no significant changes in the morphology of the skin or lungs. It
was suggested that this striking difference in morphological response was related to
the greater 'plasticity' of the larvae, which in any event undergo radical morphological
change during metamorphosis.

No published study, however, has examined haematological responses to chronic
hypoxia in larval compared with adult amphibians. The present study extends our
observations on the different responses of tadpoles and adult bullfrogs to chronic
hypoxia and hyperoxia by examining effects on the oxygen transport characteristics
of the blood.

MATERIALS AND METHODS

Experiments were carried out during the summer of 1981 on a total of 26 adult bull-
frogs (mean weight 95 ± 50 g) and on 33 tadpoles (mean weight 17 ± 5 g) of develop-
mental stages XV–XX (after Taylor & Kollros, 1946). All animals were captured loc-
ally. Both adults and larvae were divided into three populations, which were held under
hyperoxia (280–390 mmHg), normoxia (150 mmHg) or hypoxia (70–80 mmHg) at
20–23 °C for 25–28 days. Complete details of holding conditions are provided in the
companion study (Burggren & Mwalukomo, 1983). After the acclimation period, the
animal was killed, the heart was immediately exposed and a blood sample taken into
a heparinized syringe. Haemoglobin concentration was measured spectrophoto-
metrically with the cyanmethaemoglobin method. Whole blood NTP (GTP + ATP)
and 2,3-DPG concentrations were measured with u.v. spectrophotometric assays
provided by Sigma kit numbers 366-UV and 35-UV, respectively.

Whole blood O2 content was determined using the method of Tucker (1967).
Oxygen equilibrium curves at 23 °C were determined on a whole blood sample from
each individual (i.e. blood samples were not pooled). Blood was tonometered with
gases of known PO2 and PCO2 delivered by Wösthoff gas mixing pumps. The oxygen
contents at constant PCO2 (7 mmHg) and six specific values of PO2, corresponding to
approximately 10, 30, 50, 70, 90 and 100 % oxygen saturation, were determined and
used to construct the oxygen equilibrium curve. The pH of the blood at approximate-
ly 50 % saturation was measured with an IL 13 blood gas analyser. Oxygen
equilibrium curves were then repeated at a PCO2 of 14 mmHg to allow determination
of the Bohr effect.

Statistical analysis

Treatment effects (i.e. three oxygen levels) among larval populations and adu
Bullfrog respiration

populations were assessed initially by analysis of variance (ANOVA). Where significant ($P < 0.05$) treatment effects existed, differences between specific means were subsequently assessed with Student's $t$ test for independent means.

RESULTS

Haematological changes during metamorphosis in normoxia

Haemoglobin concentration increased about 1.7 times during normoxic metamorphosis (Fig. 1), while mean corpuscular haemoglobin concentration (MCHC) increased 1.2 times (MCHC, in g Hb/RBC $\times 10^{-4} = 1.70 \pm 1.04$ for tadpoles, $1.92 \pm 0.51$ for adults).

The oxygen-carrying capacity increased approximately 40% during metamorphosis, as would be predicted from the increase in Hb concentration. The Hb-O$_2$

![Figure 1](image_url)

Fig. 1. Representative oxygen equilibrium curves of the whole blood of larval (dashed lines) and adult (solid lines) bullfrogs exposed to 4 weeks of normoxia, hypoxia or hyperoxia. These curves were determined at $23^\circ$C and a P$_{CO_2}$ of 7 mmHg. The black dot on each curve represents the P$_{50}$ value.
affinity decreased greatly, with \( P_{50} \) rising from 9.4 mmHg in the tadpole to 33 mmHg in the frog (both values corrected to a plasma pH of 7.7). Metamorphosis had no effect on the cooperativity or Hill coefficient, \( n \), which was 2.5 ± 0.5 (\( N = 21 \)) in tadpoles vs 2.4 ± 0.5 (\( N = 21 \)) in adults, nor on the Bohr effect, which was \(-0.54 ± 0.19\) (\( N = 15 \)) in tadpoles and \(0.56 ± 0.37\) (\( N = 19 \)) in adults.

The concentrations of intraerythrocytic organic phosphates decreased significantly during metamorphosis, due entirely to the decrease in NTP (chiefly ATP and GTP, Bartlett, 1976, 1980). Since haemoglobin concentration increased during metamorphosis, the molar ratio of phosphate to haemoglobin decreased from 3.6 in the tadpole to 1.3 in the adult. There was no correlation between organic phosphate levels and \( P_{50} \) in either tadpoles or frogs, nor was there any significant correlation between the concentration of NTP and DPG in individual samples (\( P > 0.1 \) for correlation coefficient, \( r \)).

**Effects of hypoxia and hyperoxia on larval and adult blood**

Blood properties of adult and larval *R. catesbeiana* exposed to chronic hypoxia, normoxia and hyperoxia are indicated in Fig. 1. In the tadpole, red blood cell count, haematocrit, haemoglobin concentration, mean corpuscular haemoglobin concentration and oxygen-carrying capacity were not significantly affected by environmental \( P_{O_2} \).

In sharp contrast to larval forms, however, adult *R. catesbeiana* showed major adjustments in response to 4 weeks of hypoxia. Highly significant increases occurred in haematocrit, red cell count and haemoglobin concentration, resulting in a near doubling of oxygen-carrying capacity (Figs 1, 2). Mean corpuscular haemoglobin concentration was not significantly affected, indicating that the major response was the production of more red blood cells with comparable haemoglobin concentrations.

Intraerythrocytic phosphate concentrations were significantly lower in hypoxic tadpoles, due to a lower concentration of NTP. There was no significant difference in 2,3-DPG. There were no differences in any measured phosphates between hyperoxic and normoxic tadpoles.

No significant changes in intraerythrocytic phosphate concentrations occurred with decreasing environmental oxygen in any of the frog populations (Fig. 1).

Hyperoxia produced no significant blood changes in tadpoles or adults.

**Whole blood \( O_2 \) equilibrium curves**

Oxygen equilibrium curves for whole blood under constant, physiological conditions of pH and \( P_{CO_2} \) from hypoxic, normoxic and hyperoxic tadpoles are indicated in Fig. 2. In tadpoles, whole blood \( P_{50} \) was slightly but significantly reduced from a mean of 9.2 mmHg in normoxic animals to 7.0 mmHg after 4 weeks of hypoxic exposure. The Bohr shift and Hill’s coefficient of tadpole whole blood was not significantly affected by environmental \( P_{O_2} \) (\( P > 0.1 \), ANOVA).

The Hb-O\(_2\) affinity of the whole blood of adult frogs was unaffected by hyperoxic exposure, but hypoxic exposure produced a marked increase in affinity. The \( P_{50} \) of hypoxic frogs decreased about 35% to 24 mmHg from 35 mmHg in normoxic animals (Fig. 2). As with tadpole blood, there were no significant changes in the Bohr shift or Hill’s coefficient.
Fig. 2. Relationship between chronic ambient $P_{O_2}$ and whole blood properties of larval (dashed lines) and adult (solid lines) bullfrogs, *Rana catesbeiana*. Mean values ± 1 s.e. are given. Number of adult frogs contributing to each point are as follows: normoxic, 7; hypoxic, 6; hyperoxic, 13. Number of larvae contributing to each mean are as follows: normoxic, 9; hypoxic, 17; hyperoxic, 7. The letters (NS = not significant) or numbers beside each set of lines refers to the value for $P$, i.e., significance level, for an ANOVA of data groups for the three oxygen levels. Means which are different from the control (normoxic) means are indicated by one ($P < 0.05$) or two ($P < 0.01$) asterisks.
Table 1. Selected properties of whole blood of larval and adult bullfrogs (*Rana catesbeiana*). Appropriate references are indicated in parenthesis

<table>
<thead>
<tr>
<th>Variable</th>
<th>Tadpole</th>
<th>Adult</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haematocrit (%)</td>
<td>20·9 (1)</td>
<td>22·2 (1)</td>
</tr>
<tr>
<td></td>
<td>17·8 (6)</td>
<td>23·4 (7)</td>
</tr>
<tr>
<td></td>
<td>19·2 (8)</td>
<td>27·0 (3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>23·5 (2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>23·8 (6)</td>
</tr>
<tr>
<td>Haemoglobin (g/100 ml)</td>
<td>3·73 (1)</td>
<td>6·3 (1)</td>
</tr>
<tr>
<td></td>
<td>2·77 (6)</td>
<td>5·7 (7)</td>
</tr>
<tr>
<td></td>
<td>4·03 (8)</td>
<td>5·7 (2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6·6 (6)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6·2 (8)</td>
</tr>
<tr>
<td>ATP or NTP (µmol/ml RBC)</td>
<td>7·56 (1)</td>
<td>3·56 (1)</td>
</tr>
<tr>
<td></td>
<td>6·02 (4)</td>
<td>1·80 (6)</td>
</tr>
<tr>
<td></td>
<td>5·98 (8)</td>
<td>11·0 (5)</td>
</tr>
<tr>
<td></td>
<td>7·9 (5)</td>
<td></td>
</tr>
<tr>
<td>2,3-DPG (µmol/ml RBC)</td>
<td>2·20 (1)</td>
<td>2·29 (1)</td>
</tr>
<tr>
<td></td>
<td>4·1 (5)</td>
<td>1·79 (7)</td>
</tr>
<tr>
<td></td>
<td>0·92–2·2 (6)</td>
<td>3·3 (5)</td>
</tr>
<tr>
<td></td>
<td>3·13 (4)</td>
<td>1·10 (6)</td>
</tr>
<tr>
<td></td>
<td>4·91 (8)</td>
<td></td>
</tr>
<tr>
<td>O₂ capacity (vol %)</td>
<td>2·91 (1)</td>
<td>5·84 (1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7·15 (7)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9·2 (3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8·02 (2)</td>
</tr>
<tr>
<td>Bohr shift (ΔlogP₅₀/ΔpH)</td>
<td>-0·60 (1)</td>
<td>-0·65 (1)</td>
</tr>
<tr>
<td></td>
<td>-0·18 (8)</td>
<td>-0·18 (3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-0·29 (2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-0·18 (8)</td>
</tr>
<tr>
<td>P₅₀ (mmHg)</td>
<td>9·4 (1)</td>
<td>33· (1)</td>
</tr>
<tr>
<td></td>
<td>13 (6)</td>
<td>37· (6)</td>
</tr>
<tr>
<td></td>
<td>5·5 (8)</td>
<td>37· (7)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>42· (3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>39· (2)</td>
</tr>
<tr>
<td>Hill's coefficient (n)</td>
<td>2·5 (1)</td>
<td>2·4 (1)</td>
</tr>
<tr>
<td></td>
<td>1·8 (8)</td>
<td>2·5 (3)</td>
</tr>
<tr>
<td></td>
<td>2·8 (9)</td>
<td>1·95 (8)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2·8–3·0 (9)</td>
</tr>
</tbody>
</table>

References and physiological conditions

1. Present study. (T = 23 °C, Pco₂, 7 mmHg).
2. Lenfant & Johansen, 1967. (T = 22 °C, Pco₂, 10 mmHg).
7. Maginnis, Song & Reeves, 1980. (T = 25 °C, Pco₂, 7·83 mmHg).
8. Johansen & Lenfant, 1972. (T = 20 °C, Pco₂, 7·6 mmHg).
9. Riggs, 1951. (T = 20 °C, Pco₂, 7·3–8·4 mmHg).
DISCUSSION

Haematological changes during metamorphosis in normoxia

Our measurements of blood variables in larval and adult bullfrogs under normoxia are generally closely comparable to those reported elsewhere, with the exception of the Bohr effect (Table 1). The Bohr effect measured in this study is the same for both frogs and tadpoles and is quite high compared to that recorded from most Amphibia (Lenfant & Johansen, 1967; Sullivan, 1974). Riggs (1951) and Aggarwal & Riggs (1969) report that tadpole haemoglobin does not exhibit a Bohr effect, but their studies were performed on blood haemolysates diluted in buffers, and Watt & Riggs (1975) report that the Bohr effect measured in vitro is dependent on the buffer used. Johansen & Lenfant (1972) report low but significant Bohr effects in the whole blood of both the tadpole and adult bullfrog.

A decrease in haemoglobin oxygen affinity associated with metamorphosis, as observed in this study, is common amongst amphibians (Wood, 1971; Hattingh & Bartels, 1973; Sullivan, 1974; Johansen & Lenfant, 1972; Toews & Macintyre, 1977), though not universal (Burggren & Wood, 1981). Organic phosphates, which are important effectors in changing Hb-O₂ affinity in mammals (Benesch & Benesch, 1967; Chanutin & Churnish, 1967), are also important modulators of amphibian haemoglobins (Aggarwal & Riggs, 1969; Araki, Kajita & Shukuya, 1971; Watt & Riggs, 1975; Wood, Hoyt & Burggren, 1982). However, they were not responsible for the decrease in O₂ affinity during metamorphosis under normoxic conditions in R. catesbeiana, since the large decrease in NTP levels during metamorphosis was in the wrong direction to produce the increase in P₅₀. Rather, the change in P₅₀ is due to a change from high affinity larval haemoglobin to low affinity adult haemoglobin during metamorphosis in Rana (Riggs, 1951; Aggarwal & Riggs, 1969; Watt & Riggs, 1975; Just & Atkinson, 1972; Hazard & Hutchison, 1978). A decrease in organic phosphates with metamorphosis, as presently observed, is not universal amongst amphibians: an increase is observed in Dicamptodon ensatus (Wood, 1971) and Typhlonectes compressicauda (Garlick et al. 1979).

Effects on blood of chronic hypoxia and hyperoxia

Oxygen transfer in larval and adult R. catesbeiana maintained under chronic hypoxic conditions can potentially be enhanced by increases in the convective flow of blood and water/air through the gas exchange organs, morphological changes in the structure of the gas exchange organs, and/or adjustments in the oxygen-carrying properties of the blood. Hypoxic-induced increases in gill and lung ventilation and heart rate have been reported for Rana tadpoles (West & Burggren, 1982) and the adults of other anurans (see Boutilier & Toews, 1977 for references). However, these observations are during acute, not chronic, hypoxia and it is not known to what extent these increases in convective flow persist with time.

A companion study (Burggren & Mwalukomo, 1983) has shown that profound increases in surface area, lung volume, skin capillarization and decrease in the water/blood diffusion distance in the skin occur in response to chronic hypoxia in the tadpoles of R. catesbeiana, but that none of these morphological adjustments enhancing
gas exchange develop in the adult bullfrog. Similarly, the present study indicates a major dichotomy between larvae and adults in the haematological responses to chronic hypoxia.

No significant changes in the oxygen-carrying capacity developed in tadpoles, and the left-shift in the O₂ equilibrium curve of whole blood was probably too small to have physiological significance.

The whole blood of adult bullfrogs, however, exhibits the 'classic' responses to chronic hypoxia - a greatly increased oxygen-carrying capacity and a major left-shift in the oxygen equilibrium curve. The left-shift of the oxygen equilibrium curve cannot be ascribed to a decrease in organic phosphates, since there was no significant change in their concentrations. It is possible that some other affinity modulator caused the left-shift, or that the proportions of the various haemoglobins changed toward a predominance of high affinity types. Induction of rapid haematopoeisis by haemorrhage (Meints & Forehand, 1977) results in a higher proportion of 'larval' red blood cells, presumably carrying higher affinity larval haemoglobins. Even in the absence of an increase in convective flow of blood through the lungs and skin of the adult, such adjustments in blood properties should considerably enhance oxygen transport to the tissues during environmental hypoxia.

Hyperoxia had no effect on the oxygen transport properties of either larval or adult blood. As indicated by a lack of morphological responses to hyperoxia (Burggren & Mwalukomo, 1983), a decrease in Hb-O₂ affinity or decrease in blood O₂ capacity in response to hyperoxia would leave an animal poorly acclimated for even transient hypoxia.

This project was supported by NSF Grant PCM80-03752 (WWB) and a NSERC of Canada pre-doctoral fellowship (AP).

REFERENCES


Bullfrog respiration


