Myoglobin Levels in Some Tissues from Wild Peruvian Rodents Native to High Altitude*

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Studies on dogs (1) and guinea pigs (2) have shown increments in the myoglobin content of muscles of individuals from high altitude as compared with individuals from sea level. More recently, the same relation has been shown in man by the use of biopsy material (3), but there are no data on wild species living at high altitude. Since wild mammals often have a more vigorous life, and since they have adapted to altitude by mutation and selection over a much longer time span, their response may be quite different from the shorter term adaptation of man and domestic species. Thus, for example, an increase in blood hemoglobin is commonly seen in domestic animals and man during short term exposure to altitude, but the hemoglobin level in native species of mammals from high altitude is no higher than in those from sea level. This study surveys myoglobin levels in a series of wild mammals from the Peruvian altiplano, principally rodents, to provide some answers to this question.

EXPERIMENTAL PROCEDURE

High altitude specimens were trapped either west of Lake Titicaca (Departamento de Puno) at approximately 13,000 feet (3.9 km) or at Morococha (east of Lima) at 14,900 feet (4.5 km). The animals were then transported to Lima, where measurements of myoglobin levels were made after a sojourn of 2 weeks to 3 months. Four species each of the two dominant high altitude genera of Phyllotis (pericotes) and Akodon (grass voles) were represented. Other highland animals were the rodents, Hesperomys sorella and Chinchillidae saxamai, and the camelid alpaca (Lama pacos) and vicuña (Vicugna vicugna). In addition, values were taken on three low level mammal species: a pericote (P. darwini limatus), a rice rat (Oryzomys zanthaeolus), and a skunk (Conopatus rex inca) from near Lima; and on a rice rat (O. longicaudatus destructor) from Machu Picchu. Measurements were also made on feral house mice (Mus musculus) from both Lima and Morococha. Details on species and collections will be given later. Identifications are through the kindness of Dr. O. P. Pearson.

The procedure for myoglobin determination followed that described previously (3). Muscle samples from the leg represented a mince of all of the muscles rather than a particular muscle. Levels of cytochrome c reductase were measured in some of the rodents by procedures described earlier (4). The activity of the DPN-linked enzyme was expressed in terms of micromoles of cytochrome c reduced per minute and per gram of fresh tissue at 25°C. Nitrogen content and dry weight of the tissues were estimated by standard techniques.

RESULTS

Phyllotis—Values for the several species of Phyllotis are summarized in Table I. As is usual, values for heart were higher than for other tissues, but there was only a small difference between the low altitude P. darwini limatus and the high altitude Phyllotis (not significant). Significant differences (t > 3) were observed between high and low altitude Phyllotis for both diaphragm and leg muscles. Diaphragm from the high altitude Phyllotis contained almost as much myoglobin as heart, whereas that from the low altitude P. darwini limatus had only half that in the heart. The pooled leg muscle contained much less myoglobin, but the advantage for myoglobin in the high altitude species was almost the same as for diaphragm—a 2-fold increase. It is of interest that the highest values for heart and leg muscle and the second highest value for diaphragm were found in an individual of high altitude stock (P. darwini rupestris), which had been born and raised at sea level.

Akodon—Values for the four species of Akodon are summarized in Table II. Levels of heart myoglobin for the several species do not differ significantly from each other; nor, although the mean values are all higher, did the averages for each tissue differ significantly from the respective averages for high altitude Phyllotis. Some differences are seen for leg myoglobin, with the level of A. bolivianus significantly lower than that for both A. berlepschi and A. jelski. The values for heart, diaphragm, and leg muscle stand approximately in the ratio, 3:2:1. It is of interest that two mice from Morococha (4.5 km) showed higher individual values for each tissue when compared with mice of the respective species, A. jelski and A. bolivianus, from Puno (3.9 km).

Other Species—Myoglobin values for tissues from the remaining species are summarized in Table III. Oryzomys zanthaeolus from near Lima was notable as having one of the highest heart
TABLE I

Myoglobin levels in species of Phyllotis

Results are reported as milligrams per gram ± standard deviation (s.d.). Numbers in parentheses refer to the number of animals on which each value is based. Two values are listed when the data did not form a single distribution.

<table>
<thead>
<tr>
<th>Species</th>
<th>Heart</th>
<th>Diaphragm</th>
<th>Leg</th>
<th>Kidney</th>
<th>Liver</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>P. darwini limatus</em></td>
<td>3.90 ± 0.50 (4)</td>
<td>2.00 ± 0.81 (2)</td>
<td>0.58 ± 0.09 (4)</td>
<td>1.41</td>
<td>0.70</td>
</tr>
<tr>
<td><em>P. darwini rupestris</em></td>
<td>5.15</td>
<td>4.22</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>P. darwini chilensis</em></td>
<td>3.70 ± 0.26 (3)</td>
<td>3.95 ± 0.45 (4)</td>
<td>0.71 ± 0.15 (2)</td>
<td>1.41</td>
<td>1.71</td>
</tr>
<tr>
<td><em>P. pictus</em></td>
<td>4.70 ± 0.66 (4)</td>
<td>3.58</td>
<td>1.10 ± 0.36 (4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>P. osillae</em></td>
<td>2.70</td>
<td>2.92</td>
<td>1.17-1.29 (2)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mean ± s.d., highland species

<table>
<thead>
<tr>
<th></th>
<th>Heart</th>
<th>Diaphragm</th>
<th>Leg</th>
<th>Kidney</th>
<th>Liver</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>P. darwini limatus</em></td>
<td>4.20 ± 0.97 (9)</td>
<td>3.79 ± 0.55 (7)</td>
<td>1.27 ± 0.45 (12)</td>
<td>1.41</td>
<td>1.21</td>
</tr>
<tr>
<td><em>P. darwini rupestris</em></td>
<td>4.37 ± 0.75 (8)*</td>
<td>3.92 ± 0.42 (6)*</td>
<td>1.30 ± 0.47 (10)*</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Coefficient of variation

<p>| | | | | | |</p>
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<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>18%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLE II

Myoglobin levels in species of Akodon

Results are expressed as milligrams per gram ± standard deviation (s.d.). Whole numbers in parentheses refer to the number of animals on which each value is based. Two values are listed when the data did not form a single distribution.

<table>
<thead>
<tr>
<th>Species</th>
<th>Heart</th>
<th>Diaphragm</th>
<th>Leg</th>
<th>Kidney</th>
<th>Liver</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. amoenus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A. jelkii (Puno)</td>
<td>4.28 ± 0.85 (4)</td>
<td>2.77 ± 0.72 (3)</td>
<td>1.64 ± 0.36 (5)</td>
<td>2.34</td>
<td>1.64</td>
</tr>
<tr>
<td>A. jelkii (Morococha)</td>
<td>5.62</td>
<td>4.81</td>
<td>(4.11)*</td>
<td>1.06</td>
<td>1.17</td>
</tr>
<tr>
<td>A. berylpeschi</td>
<td>5.38 ± 0.47 (3)</td>
<td>3.28-3.76 (2)</td>
<td>1.84 ± 0.18 (3)</td>
<td>1.06</td>
<td>2.11</td>
</tr>
<tr>
<td>A. boliviensis (Puno)</td>
<td>2.94 ± 0.41 (3)</td>
<td>2.81-2.93 (2)</td>
<td>1.20 ± 0.20 (6)</td>
<td>1.35</td>
<td>1.52</td>
</tr>
<tr>
<td>A. boliviensis (Morococha)</td>
<td>4.92 ± 0.46 (3)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean ± s.d., highland species</td>
<td>4.59 ± 1.13 (15)</td>
<td>3.24 ± 0.84 (8)</td>
<td>1.43* ± 0.44 (18)</td>
<td>1.43 ± 0.54 (5)</td>
<td>1.60 ± 0.45 (5)</td>
</tr>
</tbody>
</table>

Coefficient of variation

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>26%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Akodon to highland Phyllotis ratio

<p>| | | | | | |</p>
<table>
<thead>
<tr>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.05</td>
<td>0.83</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLE III

Myoglobin levels in some Peruvian mammals

Results are expressed as milligrams per gram ± standard deviation. Numbers in parentheses refer to the number of animals on which each value is based.

<table>
<thead>
<tr>
<th>Species</th>
<th>Heart</th>
<th>Diaphragm</th>
<th>Leg</th>
<th>Kidney</th>
<th>Liver</th>
</tr>
</thead>
<tbody>
<tr>
<td>O. longicaudatus</td>
<td>3.10-4.20 (2)</td>
<td>2.01-2.35 (2)</td>
<td>0.73-1.04 (2)</td>
<td>3.52</td>
<td>2.11</td>
</tr>
<tr>
<td>O. yankinacoustus</td>
<td>6.05</td>
<td>3.25</td>
<td>0.82</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conopatus</td>
<td>4.22</td>
<td>2.90</td>
<td>5.62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mus (Lima)</td>
<td>3.50 ± 0.20 (3)</td>
<td>4.64</td>
<td>0.81 ± 0.11 (3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mus (Morococha)</td>
<td>4.45-4.57 (2)</td>
<td>2.70-3.05 (2)</td>
<td>0.89 ± 0.18 (3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hesperomys</td>
<td>5.40</td>
<td>4.22</td>
<td>1.41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chinchillala</td>
<td>4.69</td>
<td>4.22</td>
<td>1.88</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vinaña</td>
<td>6.33</td>
<td>7.97</td>
<td>5.40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alpaca</td>
<td>6.10</td>
<td>5.63</td>
<td>2.58</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Parenthesized values are not included in mean.
levels. The values for diaphragm and leg muscles in this individual were not unusual, but its liver and kidney also showed the highest values for those tissues. Although some Oryzomys are extremely active,\(^3\) this was not a particularly vigorous species. Values for O. longicaudatus from Machu Picchu were not unusual, but these two individuals were highly parasitized, in contrast to all of the other specimens in this study.

In contrast to the findings on heart myoglobin in native species, the house mice from Morococha had significantly higher myoglobin levels than those from Lima. Moreover, the animals from Morococha had much larger heart weights than those from sea level. In growing rats, guinea pigs, and dogs, the myoglobin content of heart increases with the weight of the heart and with age.\(^3\) This phenomenon, rather than the altitude, may be involved in the higher values. On the other hand, no significant increase was seen for either diaphragm or leg muscle.

Values on single individuals of Hesperomys and Chinchillula (Table III) were within the range for Akodon and the high altitude Phyllotis for all five tissues. The larger Camelidae, however, showed a somewhat different pattern. The heart myoglobin content was only slightly higher than in the rodents, but in both diaphragm and leg muscle the amounts were substantially higher—in the vicuña, by a factor of more than 2-fold. The value of 7.07 mg per g in vicuña diaphragm was the highest found in any tissue.

Our single carnivore, the mustelid Conepatus, showed the highest concentration in leg muscle of any species, but the levels in heart and diaphragm were comparable to the rodents. This was a low altitude species, and individuals of the highland subspecies (Conepatus rex rex) appeared to have even darker muscles, although it was not possible to make any analyses.

Differences in the myoglobin content of leg muscle between high and low altitude species were not related to differences in water or nitrogen content of the tissue, as has been previously reported for rats exposed to high altitude in low pressure chambers (5). Table IV shows that both the dry weight and the nitrogen content of the tissue are the same in all species regardless of the altitude of origin.

Pyridine Nucleotide-Cytochrome c Reductase—Results on a small series representing two low and five high altitude species are given in Table V. Although any conclusions concerning species must be tentative because of the small numbers, some indication of the relations is given. Values for the pooled leg muscles ranged from 31 to 52 μmoles per g per minute and showed no distinction between high and low altitude animals. The mean value in these wild species (41.7 μmoles per g per minute) was substantially higher than in the more sedentary (domestic) low altitude guinea pig (24.5 Mmoles per g per minute). The latter, however, exhibits twice as much enzymatic activity as man. The activity of the DPNH-oxidase system (micromoles of DPNH oxidized per g of N\(_2\) per minute) is 164.2 and 82.8 units for the low altitude guinea pig and for sea-level man, respectively (3, 6).

Values on diaphragm were approximately twice those on leg muscle and showed a distinct separation of high and low altitude species (101 as opposed to 71 μmoles per g per minute). This difference appears significant, in that the diaphragm is certainly involved in the extra respiratory effort at high altitude and the increase is of an appreciable magnitude (+50%).

\(^3\) Unpublished observations by B. Reynafarje on physiological variations of myoglobin during growth.

### Table IV

<table>
<thead>
<tr>
<th>Species</th>
<th>Nitrogen</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mg/g wet wt.</td>
<td>% wet wt.</td>
</tr>
<tr>
<td>Phyllotis:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lowland</td>
<td>31.5 ± 0.8 (4)</td>
<td>75.8 (3)</td>
</tr>
<tr>
<td>Highland</td>
<td>31.4 ± 1.8 (6)</td>
<td>75.9 ± 2.3 (5)</td>
</tr>
<tr>
<td>Akodon</td>
<td>31.5 ± 1.7 (11)</td>
<td>75.5 (3)</td>
</tr>
<tr>
<td>Oryzomys</td>
<td>31.1 ± 3.2 (3)</td>
<td></td>
</tr>
</tbody>
</table>

### Table V

<table>
<thead>
<tr>
<th>Source</th>
<th>Species</th>
<th>Leg</th>
<th>Diaphragm</th>
<th>Liver</th>
<th>Kidney</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowland</td>
<td>P. darwini limatus</td>
<td>39</td>
<td>63</td>
<td>261</td>
<td>283</td>
</tr>
<tr>
<td></td>
<td>O. xanthaeolus</td>
<td>47</td>
<td>79</td>
<td>283</td>
<td>168</td>
</tr>
<tr>
<td>Mean (2)</td>
<td></td>
<td>43</td>
<td>71</td>
<td>272</td>
<td>225</td>
</tr>
<tr>
<td>Highland</td>
<td>P. darwini chilenensis</td>
<td>52</td>
<td>105</td>
<td>181</td>
<td>209</td>
</tr>
<tr>
<td></td>
<td>Hesperomys</td>
<td>31</td>
<td>94</td>
<td>209</td>
<td>215</td>
</tr>
<tr>
<td></td>
<td>A. jelskii</td>
<td>42</td>
<td>94</td>
<td>203</td>
<td>180</td>
</tr>
<tr>
<td></td>
<td>A. berlepschi</td>
<td>44</td>
<td>127</td>
<td>294</td>
<td>216</td>
</tr>
<tr>
<td></td>
<td>A. boliviensis</td>
<td>45</td>
<td>96</td>
<td>283</td>
<td>283</td>
</tr>
<tr>
<td></td>
<td>A. boliviensis</td>
<td>32</td>
<td>93</td>
<td>208</td>
<td>203</td>
</tr>
<tr>
<td>Mean (6)</td>
<td></td>
<td>41</td>
<td>101</td>
<td>230</td>
<td>233</td>
</tr>
</tbody>
</table>

Values for liver were more than twice those for diaphragm (181 to 283 μmoles per g per minute) but did not differentiate the two groups; indeed, the low altitude species had a higher average enzyme content. The same situation holds for kidney, in which comparable levels were found (168 to 283 μmoles per g per minute). Although the lowest value (105 μmoles per g per minute) was found in the Oryzomys, the other low altitude species, Phyllotis darwini limatus, was at the upper limit (283 μmoles per g per minute). It may be, however, that a desert form such as P. darwini limatus requires particularly active kidney function.

### Discussion

Most authors have found a significant increase in the myoglobin content of the muscle after long term exposure of an animal to a hypoxic environment (1, 2, 5). The findings, however, are somewhat different in animals native to high altitude. Tappan and Reynafarje (2) found that native guinea pigs from high altitude had only a slightly higher myoglobin content in their muscles than those from sea level (not statistically significant). In our wild mammals, similarly, the myoglobin content of the heart was not significantly higher in species from high altitude. In diaphragm and leg muscle, however, nearly a 2-fold increase was seen. This may relate to the more active life of the wild animals as compared with the sedentary guinea pig. The very active Akodon, however, showed no higher myoglobin contents than the much quieter Phyllotis, although these two
Table VI

Ratio between enzyme concentration (Table V) and myoglobin content (Tables I to III)

<table>
<thead>
<tr>
<th>Species</th>
<th>Leg</th>
<th>Diaphragm</th>
<th>Liver</th>
<th>Kidney</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>O. xanthasolus</em> No. L</td>
<td>57</td>
<td>24</td>
<td>134</td>
<td>48</td>
</tr>
<tr>
<td><em>P. darwini limatus</em> No. 80</td>
<td>67</td>
<td>26</td>
<td>373</td>
<td>200</td>
</tr>
<tr>
<td><em>P. darwini chilensis</em> No. 32</td>
<td>29</td>
<td>26</td>
<td>106</td>
<td>148</td>
</tr>
<tr>
<td><em>Hesperomys</em> No. 1</td>
<td>22</td>
<td>22</td>
<td>184</td>
<td>184</td>
</tr>
<tr>
<td><em>A. jelskii</em> No. 12</td>
<td>24</td>
<td>24</td>
<td>124</td>
<td>77</td>
</tr>
<tr>
<td><em>A. berlepschii</em> No. 49</td>
<td>27</td>
<td>33</td>
<td>117</td>
<td>204</td>
</tr>
<tr>
<td><em>A. boliviensis</em> No. 21</td>
<td>42</td>
<td>33</td>
<td>304</td>
<td>184</td>
</tr>
<tr>
<td>&quot; No. 207</td>
<td>28</td>
<td>99</td>
<td>99</td>
<td>200</td>
</tr>
</tbody>
</table>

genera differ distinctly in their hemoglobin (hematocrit) levels. The high altitude species all show higher resting cardiac and respiratory rates than do the low altitude *Phyllotis* and *Mus* (7).

The scattered values on DPN-cytochrome c reductase in leg, liver, and kidney do not suggest any general increase in animals from high altitude. Neither is a correlation with the "activity" level of the species suggested, as has been seen in hematocrit levels. The higher enzyme concentration in the diaphragm of the "high" species may reflect the increased activity of this particular muscle in response to the increased ventilation (7), rather than an adaptation to facilitate the unloading and utilization of oxygen at a low oxygen pressure. The latter adaptation might be expected in the metabolically most active tissue, i.e. kidney, if it was to be found anywhere, but no such increase was noted. Ratios of DPN-cytochrome c reductase to myoglobin level in tissues in which both analyses were carried out are shown in Table VI. The use of this derived function does not reduce the over-all variance in the values.

SUMMARY

Highland species of *Phyllotis* (3.9 to 4.5 km) showed twice the concentration of myoglobin in diaphragm and pooled leg muscle as did a subspecies from sea level but did not differ in heart myoglobin. The more active highland *Akodon* did not differ from the high altitude *Phyllotis*. Other wild species (two high, two low) conformed to this pattern. House mice from 4.5 km showed more heart myoglobin but no more diaphragm or leg myoglobin than sea level *Mus*. Two Camelidae (vicuña and alpaca) showed slightly higher heart myoglobin and much higher diaphragm and leg myoglobin than the rodents.

REFERENCES

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Baltazar Reynafarje and Peter Morrison


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