Evolution of muscle phenotype for extreme high altitude flight in the bar-headed goose

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Bar-headed geese migrate over the Himalayas at up to 9000 m elevation, but it is unclear how they sustain the high metabolic rates needed for flight in the severe hypoxia at these altitudes. To better understand the basis for this physiological feat, we compared the flight muscle phenotype of bar-headed geese with that of low altitude birds (barnacle geese, pink-footed geese, greylag geese and mallard ducks). Bar-headed goose muscle had a higher proportion of oxidative fibres. This increased muscle aerobic capacity, because the mitochondrial volume densities of each fibre type were similar between species. However, bar-headed geese had more capillaries per muscle fibre than expected from this increase in aerobic capacity, as well as higher capillary densities and more homogeneous capillary spacing. Their mitochondria were also redistributed towards the subsarcolemma (cell membrane) and adjacent to capillaries. These alterations should improve O2 diffusion capacity from the blood and reduce intracellular O2 diffusion distances, respectively. The unique differences in bar-headed geese were much greater than the minor variation between low altitude species and existed without prior exercise or hypoxia exposure, and the correlation of these traits to flight altitude was independent of phylogeny. In contrast, isolated mitochondria had similar respiratory capacities, O2 kinetics and phosphorylation efficiencies across species. Bar-headed geese have therefore evolved for exercise in hypoxia by enhancing the O2 supply to flight muscle.

Keywords: oxygen transport cascade; high altitude adaptation; physiological evolution; exercise performance; phylogenetically independent contrasts

1. INTRODUCTION

High altitude environments are particularly challenging to animal life, owing to their characteristically low atmospheric temperatures and O2 levels. The hypoxia at high altitude can be particularly debilitating for lowland species, such that even basal metabolism is a challenge to sustain. However, numerous species have acquired genetically based physiological adaptations that minimize performance decrements at high altitude (Chappell & Snyder 1984; Beall 2007; Storz & Moriyama 2008). These species provide an exceptional opportunity for studying how complex physiological systems evolve, because the general mechanisms of O2 transport and utilization are well understood. Because the O2 transport pathway is composed of a series of cascading physiological steps (breathing, pulmonary diffusion, circulation, tissue diffusion and mitochondrial O2 utilization) (Weibel 1984), the complex nature of high altitude adaptation is best understood by considering all steps in this pathway.

One of the most celebrated high altitude performers is the bar-headed goose (Anser indicus). This species crosses the Himalayas on its biannual migration between southern and central Asia, flying over the highest mountains in the world and reaching altitudes of up to 9000 m (Swan 1970). Incredibly, bar-headed geese sustain the 10–20-fold increase in O2 consumption rate that is necessary to fuel flapping flight (Ward et al. 2002), despite the severe hypoxia at these elevations. The physiological basis for this elevated O2 transport capacity is not completely understood, but it results in part from evolutionary changes that improve O2 uptake and circulation during hypoxia (Petschow et al. 1977; Jessen et al. 1991; Scott & Milsom 2007). Much less is known about the flight muscle of this species, but theoretical modelling suggests that an enhanced capacity for O2 diffusion from blood into muscle, which can be realized with increased muscle capillarity, should also improve O2 transport in hypoxia (Scott & Milsom 2006).

Here we demonstrate, using a comparative phylogenetic approach, a striking difference in flight muscle phenotype related to high altitude flight in bar-headed geese. This difference was unique compared with multiple low altitude migratory species and was not due to physiological plasticity or interspecific variation in body mass. The unique flight muscle phenotype in bar-headed geese is therefore inherent and probably serves to improve muscle O2 transport during flight at extremely high altitudes.

2. MATERIAL AND METHODS

(a) Experimental animals

Histological measurements were made on bar-headed geese (1.9–2.7 kg), barnacle geese (Branta leucopsis) (1.6–2.2 kg) and pink-footed geese (Anser brachyrhynchus) (2.3–3.5 kg).
Mitochondrial respiration was performed on bar-headed geese, barnacle geese, greylag geese (Anser anser) (3.9–5.1 kg) and mallard ducks (Anas platyrhynchos) (1.1–1.6 kg). All birds were young adults of similar age (3–5 years old) that had been bred and raised in captivity at sea level by registered breeders. Measurements were made on both males and females for each species, none of which had ever flown.

All species in this study have a close phylogenetic relationship (figure S1, electronic supplementary material). Barnacle geese, pink-footed geese, greylag geese and mallard ducks all live at low altitudes, and although fine-scale migration patterns are not known for all of these species, they generally follow low-to-moderate altitude migration routes (Cramp & Simmons 1977).

(b) Muscle histology

Birds were terminally anaesthetized with an overdose of intravenously injected sodium pentobarbital, and the pectoralis major muscle was dissected. Samples were taken half way along the length of the sternum, 3–5 cm lateral to the carina, at surface (immediately subcutaneous), intermediate (50% depth) and deep (adjacent to the sternum) muscle depths. Samples were coated in mounting medium and then rapidly frozen in 2-methylbutane (cooled in liquid N₂). Muscle was sectioned (10 μm) transverse to fibre length in a −20°C cryostat. Additional muscle from an intermediate depth was fixed at resting length using 2.5 per cent glutaraldehyde in cacodylate buffer (0.1 M, pH 7.4), then post-fixed in buffered OsO₄ (1%) for 1 h, dehydrated in ethanol and embedded in epoxy resin. Transverse semi-thin sections (0.5 μm) were stained with toluidine blue, and ultrathin sections (approx. 80 nm) were stained with uranyl acetate and lead citrate.

Cryostat sections were stained for succinate dehydrogenase, myosin-ATPase (pre-incubated at pH 4.6) and alkaline phosphatase activities (Deveci et al. 2001), and these sections as well as the semi-thin sections (used to identify intramuscular lipid) were imaged using light microscopy. Ultrathin sections were imaged using transmission electron microscopy. Unbiased measurements for determining all histological variables were collected and analysed as described previously (Weibel 1979; Egginton 1990). Sufficient images (five or more) were analysed for each sample to account for heterogeneity, determined by the number of replicates necessary to yield a stable mean value. Mitochondria were classified as subsarcolemmal and intermyofibrillar if they were located between the cell membrane and the outer edges of peripheral myofibrils. Representative alkaline phosphatase-stained images (n = 4 for each species, surface muscle depth) were digitized to determine capillary domain area (the area around each capillary whose boundary is equidistant from each adjacent capillary) and an estimate of the heterogeneity, determined by the number of replicates (five or more) were analysed for each sample to account for intramuscular lipid). Two separate experiments were performed using two different combinations of substrates. In experiment 1, state 2 was first stimulated with malate (2 mM) and pyruvate (5 mM). P/O ratios were determined twice by the conventional method (Gnaiger et al. 2000) by adding 125 μM of ADP. After state 4 respiration was reached, state 3 was induced with maximal ADP (0.7–1.0 mM), and mitochondria were allowed to deplete all O₂. After a period of anoxia (5 min), the O₂ tension was raised, the remaining ADP was consumed and all O₂ was consumed in state 4. After anoxia, the O₂ tension was raised, cytochrome oxidase was maximally stimulated with ADP (1.25 mM), TMPD (N,N,N’,N’-tetramethyl-ρ-phenylenediamine; 0.5 mM) and ascorbate (0.5 mM) and all O₂ was consumed. After anoxia, the O₂ tension was raised and mitochondria were uncoupled with FCCP (carbonylcyanide-ρ-trifluoromethoxyphenylhydrazone; 0.5 μM). Experiment 2 was the same as experiment 1, except that succinate (10 mM) was also present to spark state 2. The O₂ tension that reduced mitochondrial respiration to 50 per cent of the normoxic rate (P₅₀) was determined for states 3 and 4, and for TMPD-stimulated respiration, as previously described (Gnaiger 2001). Respiration rates were corrected for background O₂ flux and are expressed relative to mitochondrial protein concentration.

(d) Statistical analyses

Data are generally reported as means ± s.e. One- or two-factor ANOVA and Student–Newman–Keuls post hoc tests were used, as appropriate, and abnormally distributed data were log transformed before testing. Ordinary least squares (OLS) and reduced major axis (RMA) linear regressions were used for correlations. RMA regressions were calculated with the program RMA (Bohonak & van
We used our previously published phylogenetic tree with branch lengths (Lee et al. 2008) pruned to include only the species in question (figure S1, electronic supplementary material). Low and high altitude migration strategies were coded as 0 or 1 dummy variable (Garland et al. 1992), respectively. We tested for significant positive relationships between the standardized independent contrasts of muscle traits and flight altitude by determining the one-tailed $p$-values for correlations computed through the origin (d.f. = 1 for all). Setting branch lengths to 1 yielded very similar results and is therefore not shown. A significance level of $p < 0.05$ was used throughout.

3. RESULTS AND DISCUSSION
(a) Flight muscle phenotype in geese
The flight muscle of goose contained fast oxidative (type IIa) and fast glycolytic (type IIb) fibre types, which exhibit stereotypical differences in succinate dehydrogenase (a mitochondrial enzyme) and myosin-ATPase (an index of contractility) activities (figure 1). Consistent with what is known for other bird species (Rosser et al. 1987; Torrella et al. 1998), type IIa fibres were most abundant across the muscle, and slow oxidative (type I) fibres were not observed.

There was a striking difference in the muscle fibre composition of bar-headed goose compared with the low altitude birds (figure 2 and table 1; figures S2 and S3, electronic supplementary material). The flight muscle of barnacle and pink-footed goose had a significant proportion of fast glycolytic fibres near the muscle surface, but as muscle depth increased so too did the proportion of fast oxidative fibres; this appears to be a general characteristic of birds (Mathieu-Costello et al. 1998a). In contrast, the flight muscle of bar-headed goose had a much higher proportion of fast oxidative fibres. This was apparent for average values across the whole muscle (bar-headed goose, 82.5 ± 0.9%; barnacle goose, 76.8 ± 1.0%; pink-footed goose, 71.2 ± 2.3%; d.f. = 21) and was exaggerated near the muscle surface, where the potential for increasing oxidative fibre density was greatest.

Consistent with the differences in fibre composition, the flight muscle of bar-headed goose had more capillaries than that of low altitude geese (figure 3; electronic supplementary material, figure S4). Both the number of capillaries per fibre ($C:F$) and the capillary density (CD) increased with muscle depth in barnacle and pink-footed goose. $C:F$ was much higher in bar-headed geese at surface and intermediate muscle depths, as well as for the global average (bar-headed goose, 2.13 ± 0.09; barnacle goose, 1.72 ± 0.08; pink-footed goose, 1.69 ± 0.07; d.f. = 21), such that it was as high in the superficial regions as in the deep regions. CD was also higher in bar-headed goose than in both low altitude species near the muscle surface, and the overall average was higher than in pink-footed goose (bar-headed goose, 2287 ± 112 mm$^{-2}$; barnacle goose, 2270 ± 118 mm$^{-2}$; pink-footed goose, 1802 ± 107 mm$^{-2}$; d.f. = 21). The less pronounced interspecific differences in CD than in $C:F$ probably resulted from a confounding effect of allometry on the muscle fibre size of barnacle goose (table 1; figure S5, electronic supplementary material). Nevertheless, consistent with the differences in CD near the muscle surface, the volume of muscle supplied by capillaries and their domain areas (blue), an analysed region of interest (green) and the Krogh cylinder areas for capillaries within that region (magenta) (see §2). Scale bar, 100 μm.
Because differences in fibre composition per se will influence capillarity (owing to concomitant changes in O$_2$ demands), we next sought to determine whether the increased proportion of oxidative fibres could account for the increased capillarity in bar-headed goose muscle. To do so, we first assessed the mitochondrial abundance in oxidative and glycolytic fibres in all species (figure S7, electronic supplementary material). There were no statistically significant differences between species in the mitochondrial volume densities within oxidative or glycolytic fibres, or in the densities of intramuscular or intracellular lipid droplets (table 1). Mitochondrial cristae surface densities were high (approx. 60 $\mu$m$^2$ $\mu$m$^{-2}$), similar to those in the highly aerobic flight muscle of hummingbirds (Suarez et al. 1991), but were also not different between species. With these data, we then calculated the average mitochondrial volume density at each muscle depth for each species. C:F was more strongly related to average mitochondrial volume density (figure 3) than CD (figure S8, electronic supplementary material) when only low altitude species were considered and was thus a better index for comparing capillarity between species. In doing so, we found that bar-headed geese had more capillaries per muscle fibre for a given mitochondrial volume density at surface and intermediate muscle depths. Therefore, capillarity and O$_2$ diffusion capacity are higher in bar-headed goose muscle than can be accounted for by the increased proportion of oxidative fibres.

This result has clear benefits for sustaining muscle O$_2$ flux when capillary O$_2$ tensions fall during hypoxia. Although C:F is higher in birds living at high altitude (León-Velarde et al. 1993), in some cases, this has been entirely attributed to concurrent increases in mitochondrial abundance (Mathieu-Costello et al. 1998a). Furthermore, exercise and hypoxia would have been potential stimulants of angiogenesis in these studies, in contrast to the inherently higher capillarity that exists in bar-headed geese before ever flying or experiencing high altitude. Therefore, despite some disagreement about its role during high altitude acclimatization (Mathieu-Costello 2001), increases in muscle O$_2$ diffusion capacity have evolved in some high altitude species and probably improve aerobic performance in hypoxia.

Although mitochondrial abundance within each fibre type is similar between species, the proportion of all mitochondria that are subsarcolemmal (rather than intermyofibrillar) was much higher in bar-headed geese (figure 4). Furthermore, the positive relationship between subsarcolemmal mitochondria proportion and flight altitude persisted after correcting for phylogeny ($r = 0.999$ for correlation shown in figure S6, electronic supplementary material). This redistribution of mitochondria towards the cell membrane and closer to capillaries should reduce intracellular diffusion distances. Its importance for improving O$_2$ transport is emphasized by previous human studies showing that increases in aerobic performance after exercise training are associated with a preferential proliferation of subsarcolemmal mitochondria (Hoppeler et al. 1983). In fact, the proportion of subsarcolemmal mitochondria in bar-headed goose muscle is even higher than in the highly aerobic flight muscle of hummingbirds (Suarez et al. 1991). However, this mitochondrial redistribution could hinder the
intracellular movement of ATP and other metabolites (Kinsey et al. 2007), which suggests that bar-headed goose flight muscle may need an effective system for shuttling ATP equivalents, such as the creatine kinase shuttle (Andrienko et al. 2003).

Although the mechanisms accounting for the altered muscle phenotype in bar-headed geese are unclear, they may involve inherent differences in muscle development (Bassel-Duby & Olson 2006; Biressi et al. 2007). Activity-dependent regulators of muscle phenotype (e.g. neural stimulation) did not cause the differences in this study because no species had been allowed to fly. The differences probably instead reflect evolutionary changes in the gene networks regulating skeletal muscle. Flight muscle aerobic capacity develops rapidly after birth (Bishop et al. 1995), and it is probable that bar-headed geese acquire their altered phenotype in the short time before their first migration.

**Table 1. Histological measurements from the flight muscle of geese.**

<table>
<thead>
<tr>
<th>Muscle Trait</th>
<th>Muscle Location</th>
<th>Bar-headed Goose</th>
<th>Barnacle Goose</th>
<th>Pink-footed Goose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxidative fibre numerical density (%)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>surface</td>
<td>83.5 ± 1.5&lt;sup&gt;b&lt;/sup&gt;</td>
<td>76.0 ± 1.5</td>
<td>76.4 ± 2.1</td>
</tr>
<tr>
<td></td>
<td>intermediate</td>
<td>92.5 ± 0.7&lt;sup&gt;c&lt;/sup&gt;</td>
<td>89.7 ± 1.0</td>
<td>84.2 ± 2.5</td>
</tr>
<tr>
<td></td>
<td>deep</td>
<td>95.1 ± 0.3</td>
<td>93.9 ± 0.5</td>
<td>92.2 ± 1.5</td>
</tr>
<tr>
<td>Myosin-ATPase IIA numerical density (%)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>surface</td>
<td>81.9 ± 1.3&lt;sup&gt;b&lt;/sup&gt;</td>
<td>75.0 ± 2.7</td>
<td>76.1 ± 2.8</td>
</tr>
<tr>
<td></td>
<td>intermediate</td>
<td>91.3 ± 0.7&lt;sup&gt;c&lt;/sup&gt;</td>
<td>91.1 ± 0.8</td>
<td>84.3 ± 1.8</td>
</tr>
<tr>
<td></td>
<td>deep</td>
<td>96.2 ± 0.4</td>
<td>94.6 ± 0.4</td>
<td>91.9 ± 0.9</td>
</tr>
<tr>
<td>IIA fibre transverse area (µm&lt;sup&gt;2&lt;/sup&gt;)&lt;sup&gt;d&lt;/sup&gt;</td>
<td></td>
<td>852 ± 78</td>
<td>683 ± 43</td>
<td>798 ± 45</td>
</tr>
<tr>
<td>Ib fibre transverse area (µm&lt;sup&gt;2&lt;/sup&gt;)&lt;sup&gt;d&lt;/sup&gt;</td>
<td></td>
<td>1797 ± 202</td>
<td>1504 ± 119</td>
<td>1892 ± 157</td>
</tr>
<tr>
<td>Capillary domain area (µm&lt;sup&gt;2&lt;/sup&gt;)&lt;sup&gt;e&lt;/sup&gt;</td>
<td></td>
<td>536 ± 25&lt;sup&gt;b&lt;/sup&gt;</td>
<td>648 ± 21</td>
<td>872 ± 28</td>
</tr>
<tr>
<td>Coefficient of variation for capillary spacing (%)&lt;sup&gt;e&lt;/sup&gt;</td>
<td></td>
<td>15.1 ± 0.4&lt;sup&gt;f&lt;/sup&gt;</td>
<td>20.3 ± 1.8</td>
<td>17.8 ± 1.7</td>
</tr>
<tr>
<td>IIa (fast oxidative) fibre mitochondrial volume density&lt;sup&gt;g&lt;/sup&gt;</td>
<td></td>
<td>0.053 ± 0.003</td>
<td>0.056 ± 0.005</td>
<td>0.054 ± 0.006</td>
</tr>
<tr>
<td>Ib (fast glycolytic) fibre mitochondrial volume density&lt;sup&gt;g&lt;/sup&gt;</td>
<td></td>
<td>0.056 ± 0.005</td>
<td>0.054 ± 0.006</td>
<td></td>
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<tr>
<td>Mitochondrial cristae surface density (µm&lt;sup&gt;2&lt;/sup&gt; µm&lt;sup&gt;-3&lt;/sup&gt;)&lt;sup&gt;f&lt;/sup&gt;</td>
<td></td>
<td>59.8 ± 0.9</td>
<td>61.5 ± 0.8</td>
<td>62.4 ± 1.3</td>
</tr>
<tr>
<td>IIa fibre intracellular lipid volume densities&lt;sup&gt;g&lt;/sup&gt;</td>
<td></td>
<td>0.020 ± 0.005&lt;sup&gt;h&lt;/sup&gt;</td>
<td>0.017 ± 0.003&lt;sup&gt;e&lt;/sup&gt;</td>
<td>0.051 ± 0.01</td>
</tr>
<tr>
<td>Ib fibre intracellular lipid volume densities&lt;sup&gt;g&lt;/sup&gt;</td>
<td></td>
<td>0.007 ± 0.001</td>
<td>0.008 ± 0.002</td>
<td>0.006 ± 0.003</td>
</tr>
<tr>
<td>Intramuscular lipid volume densities&lt;sup&gt;g&lt;/sup&gt;</td>
<td></td>
<td>0.024 ± 0.007</td>
<td>0.020 ± 0.003</td>
<td>0.019 ± 0.004</td>
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</table>

<sup>a</sup>n and d.f. as in figure 2.
<sup>b</sup>Significant difference from both low altitude species.
<sup>c</sup>Significant difference from just pink-footed geese.
<sup>d</sup>n as in figure 2, d.f. = 21.
<sup>e</sup>n = 4 for each species, d.f. = 11.
<sup>f</sup>Significant difference from just barnacle geese.
<sup>g</sup>n and d.f. as in figure 4.

The maximum capacities for respiration of mitochondria isolated from the flight muscle were extremely similar between bar-headed geese and low altitude species (figure 5). This was assessed for the entire electron transport chain (state 3, maximal ADP stimulation), for cytochrome oxidase (treatment with TMPD, an exogenous electron donor) and for ATP synthase (treatment with FCCP, a mitochondrial uncoupler). These results suggest that the alteration in fibre composition (figure 2), rather than any change in the respiratory or density of mitochondria within muscle cells, is the primary factor increasing aerobic capacity in bar-headed goose muscle. Bar-headed geese were also no more effective at making ATP, as indicated by an equivalent phosphorylation efficiency (indicated by the P/O ratio) to that of other species (figure 5).

The effects of low oxygen on mitochondrial respiration were largely similar between species (figure 6). This was particularly true at high respiration rates (state 3 or cytochrome oxidase stimulation), as would occur during flight exercise, although bar-headed geese had the highest mitochondrial P<sub>50</sub> at low respiration rates (state 4). Overall, the state-dependent differences in O<sub>2</sub> kinetics resulted in a strong positive relationship between P<sub>50</sub> and respiration rate across all species (figure S9, electronic supplementary material). The P<sub>50</sub> values we observed were slightly higher than those for mammalian mitochondria (Gnaiger 2001), potentially because we used a higher temperature (avian body temperature of 41°C).

There is a well-known hyperbolic relationship between O<sub>2</sub> tension and mitochondrial respiration rate (Gnaiger 2001) (shown in figure S9, electronic supplementary material). Mild O<sub>2</sub> limitation (e.g. inhibition by approx. 5–10%) will therefore occur at much higher O<sub>2</sub> tensions than P<sub>50</sub> (i.e. 50% inhibition), which was approximately 1 Torr in state 3. However, muscle intracellular O<sub>2</sub> tensions (P<sub>1/2</sub>) during intense exercise in normoxia can be well below 5 Torr in mammals (Gayeski & Honig 1988). This suggests that bird muscle mitochondria may be O<sub>2</sub> limited during flight, particularly during environmental hypoxia or vigorous exercise. This emphasizes the importance of the enhanced mitochondrial O<sub>2</sub> supply in bar-headed geese for sustaining respiration during high altitude flight.

The conservation of mitochondrial P<sub>50</sub> across species also clarifies why bar-headed geese could benefit from having more oxidative fibres. In the absence of any change in O<sub>2</sub> kinetics, improvements in muscle aerobic capacity can increase the total mitochondrial O<sub>2</sub> flux of

**b) Respiration of muscle mitochondria in geese**

The maximum capacities for respiration of mitochondria isolated from the flight muscle were extremely similar between bar-headed geese and low altitude species (figure 5). This was assessed for the entire electron transport chain (state 3, maximal ADP stimulation), for cytochrome oxidase (treatment with TMPD, an exogenous electron donor) and for ATP synthase (treatment with FCCP, a mitochondrial uncoupler). These results suggest that the alteration in fibre composition (figure 2), rather than any change in the respiratory or density of mitochondria within muscle cells, is the primary factor increasing aerobic capacity in bar-headed goose muscle. Bar-headed geese were also no more effective at making ATP, as indicated by an equivalent phosphorylation efficiency (indicated by the P/O ratio) to that of other species (figure 5).
the entire muscle at a reduced PiO2 (Hochachka 1985). In this way, having more oxidative fibres may counterbalance the inhibition of respiration by intracellular hypoxia in each individual fibre. This would make bar-headed geese less reliant on anaerobic metabolism for sustaining ATP turnover during flight in hypoxia, thus improving fatigue resistance. Their muscle may also be less inclined towards carbohydrate oxidation, as normally occurs at higher exercise intensities (McClelland et al. 1998), which is not as sustainable a fuel source for long distance migration as fats.

(c) Evolution of O2 transport for flight at high altitude

Our results are consistent with the idea that muscle phenotype evolved in bar-headed geese as an important adaptation for flying at extremely high altitudes. Increasing the capacity for O2 diffusion from the blood and reducing the intracellular diffusion distance should both improve O2 transport and thus exercise performance in hypoxia. The unique phenotype of bar-headed geese is clearly not a product of phylogenetic history: differences between low altitude species were generally small, particularly when compared with the large differences between these species and bar-headed geese; furthermore, the associations between these muscle traits and high altitude flight were independent of phylogeny. The
unique features of bar-headed geese do not result from phenotypic plasticity either, because all species were born and raised in equivalent conditions at sea level. Differences in body size had small effects on muscle fibre size, but because bar-headed geese were

\[ \text{state 3} \]

\[ P_{50} \text{ (Torr)} \]

\[ 0.5 \]

\[ 1.0 \]

\[ 0 \]

\[ 0.4 \]

\[ 0.2 \]

\[ 0 \]

\[ 2 \]

\[ \text{cytochrome oxidase} \]

\[ \text{P} \]

\[ \text{O}_2 \text{ tension} \]

\[ \text{treatment} \]

\[ \text{two-way ANOVA within each substrate combination, d.f. = 65}; \]

\[ 0.133 \text{ kPa} \]

†† represent significant differences from mallard ducks, greylag geese and mallard ducks, or all other species, respectively.

Figure 5. Mitochondria isolated from the flight muscle of bar-headed geese (\( n = 6 \), dark grey bar), greylag geese (\( n = 4 \), black bar), barnacle geese (\( n = 3 \), unfilled bar) and mallard ducks (\( n = 9 \), light grey bar) had similar respiration rates and phosphorylation efficiencies. Two different combinations of malate (mal), pyruvate (pyr) and succinate (succ) were used. (a) Significant increases in respiration occurred in all species as mitochondria were transitioned from state 2 (no ADP or ATP) to state 4 (all ADP converted to ATP), state 3 (maximal ADP stimulation) and TMPD (electron donor that maximally stimulates cytochrome oxidase) treatment, but FCCP (mitochondrial uncoupler) did not increase respiration any further (two-way ANOVA within each substrate combination, d.f. = 109; substrate combinations were not compared). (b) \( P/O \) ratios (ADP/oxygen atom consumed) were significantly lower when succinate was present (two-way ANOVA, d.f. = 43).

Figure 6. Oxygen kinetics of mitochondria isolated from the flight muscle was similar in bar-headed geese to other bird species (\( n \) and statistical features as in figure 5). Mitochondrial \( P_{50} \) is the \( O_2 \) tension that causes 50 per cent inhibition of normoxic respiration and was determined for state 3 (maximal ADP stimulation), state 4 (no ADP) and TMPD (electron donor that maximally stimulates cytochrome oxidase) treatment. Two different combinations of malate (mal), pyruvate (pyr) and succinate (succ) were used (not compared statistically). \( P_{50} \) was significantly different between respiration states (two-way ANOVA within each substrate combination, d.f. = 43). Unique features of bar-headed geese do not result from phenotypic plasticity either, because all species were born and raised in equivalent conditions at sea level. Differences in body size had small effects on muscle fibre size, but because bar-headed geese were

\[ \text{state 3} \]

\[ P_{50} \text{ (Torr)} \]

\[ 1.0 \]

\[ 0.5 \]

\[ 0 \]

\[ 0.4 \]

\[ 0.2 \]

\[ 0 \]

\[ 2 \]

\[ \text{mal–pyr} \]

\[ \text{mal–pyr–succ} \]

\[ \text{cytochrome oxidase} \]

\[ \text{P} \]

\[ \text{O}_2 \text{ tension} \]

\[ \text{treatment} \]

\[ \text{two-way ANOVA within each substrate combination, d.f. = 65}; \]

\[ 0.133 \text{ kPa} \]

†† represent significant differences from mallard ducks, greylag geese and mallard ducks, or all other species, respectively.

Proc. R. Soc. B (2009)
intermediate in mass between the two low altitude species, allometric variation cannot explain their unique muscle phenotype. It is therefore likely that the changes in muscle phenotype were uniquely derived in bar-headed geese and enhanced flight performance at high altitude. However, evolutionary forces other than high altitude adaptation could account for this change, such as genetic correlations with other phenotypes or selection for performance traits other than high altitude flight (Lauder et al. 1993). A stronger case for adaptation could be made if other high altitude waterfowl species had similar specializations for improving muscle O2 transport.

The differences in muscle phenotype and O2 diffusion capacity are part of a suite of evolutionary changes in the O2 transport pathway of bar-headed geese that improve O2 flux in hypoxia. One of these alterations, an inherently higher haemoglobin O2 affinity (Petschow et al. 1977), is known to be caused largely by a single amino acid substitution (Jessen et al. 1991; Zhang et al. 1996). This improves O2 transport in hypoxia by enhancing pulmonary O2 uptake (Scott & Milsom 2007) and assuring better O2 delivery throughout the body (Faraci et al. 1984). Pulmonary O2 uptake is also improved in bar-headed geese owing to an enhanced hypoxic ventilatory response and a more effective breathing pattern (Scott & Milsom 2007; Scott et al. 2008). Our present findings therefore imply that improvements in pulmonary loading and delivery of O2 occur in conjunction with enhanced O2 extraction from the blood by the flight muscle in bar-headed geese.

In addition to helping explain how this unique species can fly in severe hypoxia at high altitude, our present findings shed insight into how respiratory systems evolve. Early theories for how the O2 transport pathway evolves suggested that the capacity of every step in the pathway must increase equally to improve overall capacity (i.e. symmorphosis) (Weibel et al. 1991). More recent theories of respiratory pathway flux argue that overall control arises from the summed influence of each step in the pathway and that different steps have unequal contributions to control (Hochachka & Burelle 2004). This implies by extension that changes in the overall capacity for O2 transport during evolution can involve changes of varying magnitudes at different steps. Our work with bar-headed geese supports the idea that respiratory system evolution occurs through changes at multiple interacting steps in the O2 transport pathway. In the light of previous work in this species, our present data suggest that the physiological traits having the greatest control over O2 transport in hypoxia (Scott & Milsom 2006) are also the most likely to evolve and improve exercise performance at high altitudes.

4. CONCLUSIONS

Our present findings suggest that O2 diffusion capacity in the flight muscle is enhanced in bar-headed geese, owing to both an increase in the number of capillaries surrounding each muscle fibre and a redistribution of mitochondria towards the cell membrane within the fibres, and thus closer to capillaries. Muscle aerobic capacity is also improved by an increased proportion of oxidative fibres, but properties of mitochondrial O2 demand are otherwise conserved between species. The flight muscle of bar-headed geese has therefore evolved for exercise in severe hypoxia by enhancing muscle O2 supply, which may be especially important for this species’ incredible ability to fly high.

All animal care and experimentation was conducted according to UBC animal care protocol no. A04-1013.

We gratefully acknowledge R. D. H. Barrett, N. A. Fangue, A. Y. Fong, T. Garland, D. Horne, W. P. Maddison, F. Syeda and S. J. Thornton for technical advice and assistance, A. Vanderhorst and P. Jones for assistance with animal care and two anonymous referees for excellent comments on an earlier version of this manuscript. This work was funded by Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grants to W.K.M. and J.G.R., a Natural Environment Research Council grant to S.E. and NSERC, Killam Trust and IODE Canada scholarships to G.R.S.

REFERENCES


Proc. R. Soc. B (2009)


