Basal metabolic rate and the mass of tissues differing in metabolic scope: migration-related covariation between individual Knots Calidris canutus

Thomas P. Weber and Theunis Piersma


To examine whether variability in the basal metabolic rate (BMR) of migrant shorebirds is a function of a variably sized metabolic machinery or of temporal changes in metabolic intensities at the tissue level, BMR, body composition and activity of cytochrome-c oxidase (CCO, a marker for maximum tissue respiration) were measured in 14 captive Knots Calidris canutus canutus in late spring, during the period of mass loss after the migratory body mass peak. Although the body mass cycle of captive birds closely followed the changes of free-living conspecifics, their fat-free mass of muscles and organs was somewhat lower and their fat content higher. BMR significantly declined during mass loss, as did the fat-free dry mass. BMR was an allometric function of both body mass (exponent = 0.687) and lean dry mass (exponent = 1.132). Fat-free dry mass of heart and flight muscle decreased with the loss of fat. CCO-activity was determined in heart, flight muscle, leg muscle, liver and kidney. It was highest in heart and flight muscle and low in the other tissues. CCO-activity was not correlated with total fat mass. Intraspecific migration-related variation in BMR seems better explained by variation in the mass of organs with a high metabolic scope (as indicated by high CCO-activity), than by variation in the intensity of tissue metabolism.

T. P. Weber, Zoological Laboratory, University of Groningen, P.O. Box 14, 9750 AA Haren, The Netherlands, and BSRC/NERC Ecology and Behaviour Group, Department of Zoology, University of Oxford, South Parks Road, Oxford OX1 3PS, U.K.

T. Piersma (corresponding author), Netherlands Institute for Sea Research (NIOZ), P.O. Box 59, 1790 AB Den Burg, Texel, The Netherlands, and Zoological Laboratory, University of Groningen, P.O. Box 14, 9750 AA Haren, The Netherlands. E-mail: theunis@nioz.nl

The basal metabolic rate (BMR), i.e. the rate of energy utilization of postabsorptive homeothermic animals under thermoneutral conditions (Aschoff and Pohl 1970), is a key concept in the study of avian energetics. BMR is commonly used as a reference point to evaluate energy intake or expenditure. For example, values for the ratio between daily energy expenditure and BMR during breeding (Drent and Daan 1980, Bryant and Tatner 1991), and between sustained metabolic rate and BMR (Peterson et al. 1990), usually fall between 1.5 and 5. Short term peak rates can yield much higher ratios (Bartholomew 1977, Peterson et al. 1990).

However, even when BMR is measured in a standardized way (see e.g. Aschoff and Pohl 1970, Hayes et al. 1992), it varies in the course of the annual cycle of a bird. In fact, seasonally variable BMR-levels (e.g. Wijnandts 1984, Dietz et al. 1992) may explain part of the inter- and intraspecific variation in the reported ratios between energy expenditure and BMR. Recently, Piersma et al. (1995) demonstrated that BMR of captive individuals of a long-distance migrant shorebird species, the Knot Calidris canutus, peaked when body mass was high during the period of northward migration. BMR of Knots in early June increased by 40% above their average level during the rest of the year.
Long-distance flight is energetically demanding. A multitude of physiological mechanisms allows birds to meet these demands, many related to the storage and subsequent mobilization of large amounts of fat (Blem 1990, Ramenofsky 1990, Jenni-Eiermann and Jenni 1992). There is also considerable flexibility in organ (including muscle) sizes (Davidson and Evans 1986, Evans et al. 1992, Piersma et al. 1996). For example, large fuel stores may require a large musculature for transport (Pennycuick 1978, Piersma 1990, Piersma and Jukema 1990, Lindström and Piersma 1993). Studies on mammals have indicated that a large part of BMR is generated by the brain and by the organs in the abdominal cavity (Aschoff et al. 1971, Schmidt-Nielsen 1990). However, since muscle tissue accounts for some 20% of the lean mass of Knots (pers. obs.), even small variations in muscle mass and muscle respiration could affect BMR. The high level of muscular activity during long-distance migration also requires a high level of support in the form of fuel supply and waste degradation by the organs in the abdominal cavity (Kersten and Piersma 1987, Jenni-Eiermann and Jenni 1991). It is therefore possible that migration-related changes in the size of these organs additionally explain variable BMR-levels (Piersma et al. 1996).

Enzymatic or biochemical characteristics have been employed frequently to investigate tissue-specific responses to exercise, environment and events in the annual cycle (Holloszy 1975, Marsh 1981, Dawson et al. 1983, Lundgren and Kiesling 1985, 1986, Butler and Turner 1988, Carey et al. 1989, Saunders and Klemm 1994, O’Connor 1995). An indirect method to quantify tissue respiration is measurement of the activity of cytochrome-c oxidase (CCO), the terminal step in the electron transport system. This approach is implicitly based on the concept of symmorphosis, which states that morphological structures, biochemical pathways and enzyme concentrations will develop and be maintained to the degree required for meeting maximum demands (Taylor and Weibel 1981; a critique of this concept is given by Dudley and Gans 1991). The enzymatic approach offers a straightforward alternative to conventional in vitro respirometry which is affected by the method of tissue preparation (Oikawa and Itazawa 1983) and medium composition (Krebs 1950). In vitro respirometry gives oxygen consumption rates at basal level, whereas, according to the principle of symmorphosis, enzyme activities should reflect maximum levels. Yet, in mammals CCO-activity seems well correlated with in vitro oxygen consumption rates for different tissues (Simon and Robin 1971), a relationship which, to our knowledge, has not been established for other enzymes frequently used as markers for metabolic activity. The way in which physiological adjustments affect BMR depends on the extent to which BMR is a function of (1) the mass of the metabolically active parts of the body, (2) the intensity of tissue metabolism, or (3) a combination of (1) and (2). If BMR is only a function of the mass of metabolically active (fat-free) tissue (e.g. Scott and Evans 1992) measuring the trajectories of fuel gain in terms of fat and fat-free tissue (Lindström and Piersma 1993, Van der Meer and Piersma 1994) would be the only requirement for estimates of migration-related changes in basal expenditure and metabolic scope, parameters which are relevant for understanding constraints on fuel deposition rates (Lindström 1991). To test hypotheses (1)–(3), we have measured BMR, CCO-activity in selected tissues and the dynamics of body composition in captive Knots during and after the period of peak mass in connection with their (non-executed) northward migration. The necessity to relate seasonal changes in metabolic performance and body composition to known circannual history forced us to use partially restrained, rather than free-living, individuals.

Material and methods

Experimental animals

Measurements were carried out during June 1992 on 14 adult Knots of the subspecies C. c. islandica (see Piersma et al. 1991, Davidson and Wilson 1992, Piersma and Davidson 1992 for reviews of this and other subspecies, and their migrations and annual cycles). The birds had been captured in the Wadden Sea during October-March, 1–3.5 years earlier, and were kept in outdoor aviaries (2 m × 4 m × 1.8 m) at the Zoological Laboratory in Haren, The Netherlands (53°11’N, 06°36’E), in groups of 4–8 individuals. Floors of the aviaries were covered with regularly refreshed sand. A 30 cm by 60 cm basin with continuously flowing water gave the birds the opportunity to drink and bathe. The birds were fed protein-rich (45% of fresh mass) trout food pellets ad libitum. At weekly intervals all the birds were weighed to the nearest 0.1 g on a Sartorius electronic balance, checked for injuries and scored for body-moult. All the Knots maintained a clear circannual body mass cycle and a normal pattern of moult and plumage changes (Piersma et al. 1995). They showed enhanced flight activity in the cages during the normal migration periods (pers. obs.).

BMR measurements

Twenty-four hours prior to the experiment, the birds were transferred to a separate outdoor cage, where they were kept without food but with fresh water. Since the throughput time of food in the gut of Knots is 2 h at most, this procedure ensured that the birds were post-absorptive at the start of the oxygen measurements. Before entering the respiratory chambers of 15 or 20 l,
the birds were weighed to the nearest 0.1 g, and then placed individually in temperature-controlled cabinets at 25°C, i.e. within the thermoneutral zone of Knots (Wiersma et al. 1993). Dry air was pumped into the sealed chamber. Flow rates were set at approximately 90 l/h (for the 15 l chamber) or 120 l/h (20 l chamber) and measured on the dry inlet air with a Mass Flow Controller (Brooks Instruments, Veenendaal, The Netherlands, Model 5850E) with an accuracy of 0.4%. Gas analyses were performed on samples of inlet and outlet gases, both dried with a molecular sieve (3 Å, granules approximately 2 mm; Merck). The oxygen concentration of the dried ingoing and outgoing air was measured by an oxygen analyser (AMETEK Applied Electrochemistry Pittsburgh, PA, USA, Models S-3A and S-3A/II) with an accuracy of 0.002%. Calibration was performed using dry, oil-free air mixtures. The use of a mass flow meter made it unnecessary to transform the data to standard temperature and pressure. Oxygen consumption in ml/h was calculated after Hill (1972). As post-absorptive Knots had an RQ of approximately 0.73 (T. Piersma, L. Bruinzeel and P. Wiersma, unpubl. data), the energy equivalent per volume oxygen was taken as 20 kJ/O₂ (Gessaman and Nagy 1988, Schmidt-Nielsen 1990).

The measurements started between 18 and 20 hours, and ended around 09 hours the following morning, when the birds were reweighed. The data were checked immediately and BMR was estimated from a 60 min running mean of oxygen consumption rate (see Piersma et al. 1995 for details). The birds were then killed by cervical dislocation. Parts of flight muscle, leg muscle, kidney, liver and the whole heart were dissected in this fixed sequence. They were frozen in liquid nitrogen as quickly as possible, the whole procedure taking a maximum of 10 min. The tissue samples were stored at −80°C until further analysis. The rest of the carcass was either directly dissected into body components, or first stored in air-tight plastic bags at −18°C for a few weeks before dissection.

Body composition analysis

All flight and contour feathers were plucked and the naked carcass dissected. The sex of the bird was determined by gonadal inspection. The different organs were taken out (see Summers et al. 1992, Piersma et al. 1996 for details) and dried separately to constant mass at 55–60°C. Flight muscle refers here to the combination of the m. pectoralis and the m. supracoracoideus. Each component was reweighed, packed in filter paper and the fat extracted in a Soxhlet apparatus using petroleum-ether (boiling trapez 40–60°C) as a solvent for 8 to 24 h depending on the size of the component, dried at 55–60°C and weighed again. The loss of dry mass during fat extraction was taken as the extracted fat mass. The values for leg muscle, flight muscle, kidney and liver were corrected for the parts removed for the enzyme assays. The fat-free dry mass of the heart was estimated from fresh mass on the basis of data from carcass analyses of other samples of Knots (T. Piersma, unpubl. data).

To evaluate the absolute masses of the various body parts, the values for the captive birds were compared with the values of a similarly analysed wild Knot, collected a few days after its arrival in the breeding areas in the Canadian High Arctic on 10 June 1990 (Alert, Ellesmere Island, 82°30’N, 62°W).

Measurement of CCO-activity

Tissue samples were thawed, weighed, washed in isotonic medium and then transferred into 30 ml of cold Na-K-Phosphate buffer (0.03 M) at pH 7.4. Aprotinin (final concentration 2 µg/ml) and phenylmethylsulfonylfluoride (PMSF; final concentration 100 µg/ml) were added as proteinase inhibitors. The tissues were then homogenized mechanically for 2 min with an Ultrathurax® homogeniser. Two samples of 500 µl of each tissue were taken and n-dodecyl b-D-maltosid added as detergent (final concentration 0.75%). The samples were incubated for 15 min at room temperature and subsequently centrifuged at 0–4°C at 1200 g for 20 min. The supernatant, avoiding the surface lipid layer, was used for analysis of the CCO-activity. The assay method used is based on the oxidation of reduced cytochrome-c (Cooperstein and Lazarov 1950, Simon and Robin 1971). The reaction was monitored by following the decline in absorbency at 550 nm of a solution of reduced cytochrome-c using a Beckmann DU-7 spectrophotometer. Assays were conducted at room temperature (20–22°C). Samples were diluted until a linear decrease in absorbency over 2–3 min could be observed. CCO-activity was expressed as nmol of cytochrome-c oxidised per min per mg of extracted tissue protein. A zeroth order reaction was assumed. We used a millimolar extinction coefficient of 29.5 for reduced cytochrome-c (Goolish and Adelmann 1987). The protein concentration of the supernatant was determined with the Pierce BCA-Proteinassay® (Pierce, Rockford, Illinois, USA), using bicinchoninic acid (Smith et al. 1985).

Statistics

Statistical analyses were carried out in StatView®. We used one-tailed significance tests where we had a hypothesis about the direction of a correlation.
Table 1. Summary data for sex (F = female, M = male), mass and BMR of the captive Knots used in this study. We failed to identify the sex of #620.

<table>
<thead>
<tr>
<th>Bird ID</th>
<th>Sex</th>
<th>Peak mass (g)</th>
<th>Mass at measurement (g)</th>
<th>Days after peak mass</th>
<th>BMR (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#412</td>
<td>F</td>
<td>195.0</td>
<td>192.3</td>
<td>2</td>
<td>0.91</td>
</tr>
<tr>
<td>#001</td>
<td>F</td>
<td>182.2</td>
<td>179.0</td>
<td>4</td>
<td>0.97</td>
</tr>
<tr>
<td>#237</td>
<td>F</td>
<td>163.4</td>
<td>155.7</td>
<td>4</td>
<td>0.95</td>
</tr>
<tr>
<td>#371</td>
<td>M</td>
<td>176.4</td>
<td>163.3</td>
<td>4</td>
<td>1.33</td>
</tr>
<tr>
<td>#408</td>
<td>F</td>
<td>192.1</td>
<td>146.4</td>
<td>8</td>
<td>1.42</td>
</tr>
<tr>
<td>#370</td>
<td>M</td>
<td>164.5</td>
<td>154.9</td>
<td>9</td>
<td>0.93</td>
</tr>
<tr>
<td>#306</td>
<td>F</td>
<td>186.5</td>
<td>177.5</td>
<td>15</td>
<td>0.97</td>
</tr>
<tr>
<td>#372</td>
<td>F</td>
<td>192.2</td>
<td>165.6</td>
<td>20</td>
<td>0.84</td>
</tr>
<tr>
<td>#620</td>
<td>?</td>
<td>164.6</td>
<td>110.9</td>
<td>21</td>
<td>0.65</td>
</tr>
<tr>
<td>#405</td>
<td>F</td>
<td>184.6</td>
<td>113.9</td>
<td>21</td>
<td>0.80</td>
</tr>
<tr>
<td>#621</td>
<td>M</td>
<td>214.2</td>
<td>98.3</td>
<td>24</td>
<td>0.65</td>
</tr>
<tr>
<td>#154</td>
<td>M</td>
<td>165.8</td>
<td>124.8</td>
<td>28</td>
<td>1.00</td>
</tr>
<tr>
<td>#373</td>
<td>F</td>
<td>178.4</td>
<td>132.1</td>
<td>28</td>
<td>0.81</td>
</tr>
<tr>
<td>#616</td>
<td>M</td>
<td>152.7</td>
<td>93.6</td>
<td>31</td>
<td>0.68</td>
</tr>
</tbody>
</table>

Results

The Knots reached maximum body mass between 22 and 29 May (Table 1), exactly as their free-living conspecifics (Wilson and Morrison 1992). Peak body mass varied between 152.7 and 214.2 g (mean = 179.5 g, SD = 16.3). There was no difference in peak mass between the sexes; the mean was 174.7 g for males (SD = 23.61, N = 5), and 184.3 g for females (SD = 10.13, N = 8; Student’s t-test, t = 1.026, P = 0.33). Body mass immediately before the BMR measurements varied between 93.6 and 192.3 g. The mass loss after migration-related peak levels is a consequence of voluntary reductions in food intake (cf. Kersten and Piersma 1987). Average mass loss, based on the individual rates, was 2.17 g/day (SD = 1.45). The highest rate of loss was incurred by bird #408 with 5.71 g/day.

Among the individuals, body mass decreased significantly with time (Fig. 1A) (body mass [g] = 181.3 - 2.44 time [days], N = 14; r² = 0.619; slope: SE = 0.552, t = -4.419, P = 0.0008). Most of this mass loss was attributable to fat since the slope of the relationship between total fat and time was -1.81 g/day (N = 14; r² = 0.602; SE = 0.425, t = -4.260, P = 0.0011, Fig. 1C). These two slopes are not significantly different (t = 0.42, df = 24, P > 0.25). Total fat-free dry mass (FFDM) also decreased significantly with time (Fig. 1B) (FFDM [g] = 41.21 - 0.27 time [days], N = 14; r² = 0.47; slope: SE = 0.081, t = -3.266, P = 0.007). BMR measurements were conducted from 2 to 31 days after the date of mass (Table 1).

BMR varied between 0.65 W and 1.42 W, and showed a significant decrease with time after peak mass (Fig. 2) (BMR [W] = 1.131 - 0.014 time [days], N = 14; r² = 0.37; t = -2.652, P = 0.0211). BMR showed a significant linear relationship with total body mass in a double-logarithmic scale (Fig. 3A) (log BMR [W] = -1.523 + 0.687 log body mass [g], N = 14; r² = 0.442; intercept: SE = 0.478, t = -3.184, P = 0.0079; slope: SE = 0.223, t = 3.082, P = 0.0095). This slope is statistically indistinguishable from the slope (0.729) of an interspecific regression for six shorebird species, not including the Knot (Kersten and Piersma 1987).
Total body mass includes many components with low or no metabolic activity, especially fat (Scott and Evans 1992) and water. Fat-free dry mass rather than total body mass should reflect the metabolically active tissue (Piersma et al. 1996). The slope of the double-log regression between BMR and fat-free dry mass was statistically significant in a one-tailed test (Fig. 3b) (log BMR [W] = \(-1.823 + 1.132 \log \text{FFDM} \ [\text{g}], \ N = 14; \ r^2 = 0.255; \text{SE} = 0.875, t = -2.082, \text{P} < 0.05\). Remarkably, however, BMR and total fat mass showed an even stronger relationship (log BMR [W] = \(-0.296 + 0.17 \log \text{fat} \ [\text{g}], \ N = 14; \ r^2 = 0.538\). Regressing the residuals of the double-log regression of BMR and fat-free dry mass against the logarithm of fat mass gives a significant relationship in a one-tailed test (residuals = \(-0.151 + 0.105 \log \text{fat} \ [\text{g}], \ N = 14, \ r^2 = 0.272; \ t = 2.119, \text{P} < 0.05\)).

To answer the question which physiological mechanism may cause the observed change in BMR with body mass and time, we looked for variations in fat-free dry mass and CCO-activity of the tissues. To take interindividual differences in the timing of programmed mass changes into account, we used total fat as the independent (temporal) axis (Van der Meer and Piersma 1994). Fat mass and FFDM showed a significant positive correlation (r = 0.669, P = 0.0072). Of the tissues used in the enzyme assay, only the fat-free dry mass of heart (r = 0.664, P = 0.0079) and flight muscle (r = 0.742, P = 0.0015) showed significant correlations with fat mass (Fig. 4); the value for leg muscle mass was r = 0.166, P = 0.58, for liver r = 0.27, P = 0.36, and for kidney r = 0.248, P = 0.4.

To get a general idea about the relative metabolic intensity characterizing the investigated tissues, all the values of the CCO-activity for each tissue type were pooled and the mean calculated (Fig. 5). There are significant differences in activity; because the variances are not homogeneous the original data were log-transformed to carry out an ANOVA (F = 24.921, P < 0.0001). Two groups of tissues can be distinguished clearly: heart and flight muscle have a much higher activity than the three other tissues. There is no significant difference in the activity of heart and flight muscle (Scheffé’s test, P = 0.79) and no significant difference between the other three tissues (Scheffé’s test for all pairs, P = 0.99). Heart and flight muscle are significantly different from the three other tissues (Scheffé’s test, P < 0.0001 for all pairs).

Generally, the values for the CCO-activities were variable. Using untransformed data, the coefficients of variation (SD/mean) are 66.5% for heart, 80.8% for flight muscle, 54.3% for leg muscle, 46.8% for liver and 44.4% for kidney. To see if some of this variation is a consequence of changes in total body mass and fat load, Fig. 6 gives CCO-activity in relation to fat mass. None of the tissues exhibited a significant correlation between CCO-activity and fat load (N = 14; heart: r = \(-0.008, P = 0.98\); flight muscle: r = \(-0.269, P = 0.36\); leg muscle: r = 0.343, P = 0.31; liver: r = 0.334, P = 0.25; kidney: r = 0.148, P = 0.62).

In heart and flight muscle, protein content per gram fresh mass varied neither with body mass (heart: r = \(-0.449, P = 0.11\); flight muscle: r = 0.018, P = 0.95) nor with fat mass (heart: r = \(-0.373, P = 0.19\); flight muscle: r = 0.054, P = 0.86). The mean level for heart muscle (N = 14) was 0.103 ± 0.011 g protein/g and for flight muscle (N = 13) 0.139 ± 0.043 g protein/g (mean ± SD).
**Discussion**

This study confirms that BMR of Knots varies a great deal during the migration season (Piersma et al. 1995). The measured values of BMR are mostly lower than 1 W, the predicted value of BMR for a shorebird such as a Knot (Kersten and Piersma 1987). One critical assumption in many studies on avian energetics is that the metabolic rates of captive birds are similar to those

---

**Fig. 4.** The fat-free dry masses of the tissues used in the enzyme assays, as a function of total fat mass of Knots.

**Fig. 5.** The CCO-activity (in nmol substrate oxidized per min per mg of extracted tissue protein) of the tissues (of Knots) used in the enzyme assay as a function of total fat mass.
cycles of free-living Knots are maintained by birds in captivity (Piersma et al. 1995), and we have evidence that such circannual cycles are endogenously controlled (Cadée et al. 1996).

The slope of the allometric relationship between BMR and body mass is close to the value of 0.67 deduced by Heusner (1982) on the basis of theoretical considerations. However, the basic assumption of his argument (no change in body composition), is clearly not met. The slope of BMR on fat-free dry mass is considerably steeper than 0.67. Similarly high values were found by Daan et al. (1989) for an intraindividual comparison in Kestrels Falco tinnunculus. This means that heavy birds have an energy turnover considerably above that expected from homomorphic change (Heusner 1987). It is likely that this is a consequence of a disproportionate increase in the mass of metabolically active tissue.

Interestingly, the ranking of the tissues according to enzyme activity differs from the rank order of oxygen consumption reported in the literature. Field et al. (1989) and Simon and Robin (1971) found the highest oxygen consumption rates in heart and kidney. In contrast, Else and Hurlbert (1981) found only very small differences in CCO-activity between liver, kidney, and heart of the mouse Mus musculus, but they calculated activity with respect to wet mass. Kidney and liver had very low activities in our experiments. Differences between birds and mammals, and differences in the content of extractable protein of organs could possibly explain some of the discrepancies.

Although we found no significant fat-mass related changes in mass-specific aerobic capacity, mass-specific changes in metabolic rate cannot be completely ruled out. CCO-activity values were variable and sample sizes were quite low. Dimarco et al. (1987) report that coefficients of variation of CCO-activities of human tissues are in the range of 32–42%. Given that the determination of protein is a further experimental step that introduces some error, our values and their variability (CV = 44–81%) are not unusual. Note further that there is a non-linear, accelerating relationship between CCO-activity and tissue respiration (Simon and Robin 1971). Small changes in enzyme concentrations can, therefore, go together with large changes in oxygen consumption. The enzyme assay may not have been sensitive enough.

Lundgren and Kiessling (1986) showed a higher activity of CCO in the pectoralis muscle of migratory Reed Warblers Acrocephalus scirpaceus than in pre-migratory individuals. In contrast, there were no migration-related changes in mass-specific oxidative capacity of pectoralis muscles in Semipalmated Sandpipers Calidris pusilla (Driedzic et al. 1993) and Gray Catbirds Dumetella carolinensis (Marsh 1981). Furthermore, no changes in oxidative capacity of the pectoralis muscle associated with winter acclimatization have been de-
Table 2. Body composition of the captive Knots used in this study, and a comparison between a wild-captured bird after arrival from migration on the breeding grounds in arctic Canada (10 June 1990, Alert, Ellesmere Island, NWT) and the average of two similarly weighing experimental birds (#373 and #154). Note that total body mass of the wild bird has been adjusted to the average water% of fat-free mass of the, slightly dehydrated, captive birds (65.2%). Bill length in mm, all mass values in g. FFDM = fat-free dry mass.

<table>
<thead>
<tr>
<th>Variable</th>
<th>All captive birds (n = 14)</th>
<th>#373 &amp; #154 (captivity)</th>
<th>#1052 (Alert)</th>
<th>Ratio Alert/captivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>SD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bill length</td>
<td>31.85</td>
<td>2.35</td>
<td>31.0</td>
<td>32.8</td>
</tr>
<tr>
<td>Body mass</td>
<td>142.74</td>
<td>31.24</td>
<td>128.45</td>
<td>128.19</td>
</tr>
<tr>
<td>Total fat mass</td>
<td>39.44</td>
<td>23.52</td>
<td>36.55</td>
<td>12.47</td>
</tr>
<tr>
<td>Total FFDM</td>
<td>37.98</td>
<td>3.58</td>
<td>36.55</td>
<td>42.55</td>
</tr>
<tr>
<td>FFDM-5 organs</td>
<td>9.22</td>
<td>1.21</td>
<td>8.56</td>
<td>11.77</td>
</tr>
<tr>
<td>Breast FFDM</td>
<td>6.97</td>
<td>1.06</td>
<td>6.46</td>
<td>8.47</td>
</tr>
<tr>
<td>Breast Fat</td>
<td>1.63</td>
<td>0.83</td>
<td>1.46</td>
<td>0.98</td>
</tr>
<tr>
<td>Leg FFDM</td>
<td>0.97</td>
<td>0.19</td>
<td>0.95</td>
<td>1.36</td>
</tr>
<tr>
<td>Leg Fat</td>
<td>0.79</td>
<td>0.39</td>
<td>0.85</td>
<td>0.45</td>
</tr>
<tr>
<td>Heart FFDM</td>
<td>0.43</td>
<td>0.06</td>
<td>0.43</td>
<td>0.61</td>
</tr>
<tr>
<td>Heart Fat</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liver FFDM</td>
<td>0.58</td>
<td>0.09</td>
<td>0.54</td>
<td>0.89</td>
</tr>
<tr>
<td>Liver Fat</td>
<td>0.24</td>
<td>0.12</td>
<td>0.33</td>
<td>0.14</td>
</tr>
<tr>
<td>Kidney FFDM</td>
<td>0.26</td>
<td>0.16</td>
<td>0.19</td>
<td>0.44</td>
</tr>
<tr>
<td>Kidney Fat</td>
<td>0.16</td>
<td>0.10</td>
<td>0.25</td>
<td>0.07</td>
</tr>
<tr>
<td>Rest FFDM</td>
<td>30.36</td>
<td>2.86</td>
<td>28.00</td>
<td>30.78</td>
</tr>
<tr>
<td>Rest Fat</td>
<td>36.62</td>
<td>22.33</td>
<td>29.22</td>
<td>10.83</td>
</tr>
</tbody>
</table>

tected for two finch species (Marsh and Dawson 1982, Carey et al. 1989). The observation that the residuals of the regression of BMR on FFDM were correlated with fat mass may suggest that (1) birds carrying high fat loads show increased metabolic intensity of the active tissue or that (2) fat is not entirely metabolically inert, or (3) a combination of (1) and (2).

If we consider CCO-activity as an indicator of metabolic scope, our results showed that the "temporal" (as indicated by fat mass) decline in BMR corresponds with a decrease in the mass of those organs with the highest metabolic scope, i.e. heart and flight muscle. These two tissues comprise the most important parts of the machinery for active flight (Burton 1990). In double-log regressions, fat-free dry masses of heart and flight muscle were both positively correlated with BMR, but only for heart the relationship with BMR was statistically significant (log BMR [W] = 0.298 + 0.948 log FFDMheart [g]; N = 14; r² = 0.344, t = 2.511, P = 0.027). We propose that migration-related variations in BMR are mainly due to variations in the size of organs capable of generating a high working level. This mechanism would provide the causal basis for the empirical correlations between BMR and maximum sustained working level reported in the literature (Daan et al. 1990).

Migration-related changes in BMR thus represent secondary adjustments to the demands of migration, because the tissues that vary in mass are precisely those that enable a high flight performance. The present findings extend the conclusion of Piersma et al. (1996) that inraspecific variations in BMR of overwintering Knots (i.e. individuals that are not actively migrating) are correlated with, and effects of variations in, the size of the nutritional organs (the gut, liver and kidneys). Depending on seasonal context, adaptive size variation in the nutritional as well as the "exercise" organs (muscles and heart) can thus modify the level of BMR.

Acknowledgements – We are greatly indebted to Dr Anke Huckriede and Dr Etienne Ageribibe of the Department of Physiological Chemistry, University of Groningen, for generously providing space, instruments and much advice for the enzyme analyses, and for tolerating an ecologist in their molecular biology lab. Leo Bruinzeel gave indispensable help with some of the experiments and introduced TPW to the respirometry unit. Gerard Overkamp was always available when there were technical problems. The team of Ebel Nieboer at Schiermonnikoog captured most of the birds, while Niels Cadée, Nanette Verboven and Leo Bruinzeel took care of them in captivity. Through the good offices of, and joint field efforts with, R. I. Guy Morrison of the Canadian Wildlife Service, and the hospitality of the Canadian Forces at CFS Alert, TP was able to obtain detailed body composition data of a pre-breeding Knot from June. Ulrike Müller was of constant moral support and valuable help throughout the work. We gratefully acknowledge comments and criticisms during manuscript preparation by A. Lindström, M. Klaassen, P. Wiersma, P. R. Evans, L. Bruinzeel, H. Biebach, S. Jenni-Eiermann and referees. TPW was financially supported by a Deutscher Akademischer Austausch Dienst (DAAD) doctoral scholarship under their Hochschulsprisenprogramm II. This is publication number 3030 of NIOZ, Texel.

References


1987. What does the power function reveal about structure and function in animals of different size? – Annu. Rev. Physiol. 49: 121–133.


Piersma, T. 1990. Pre-migratory “fattening” usually involves more than the deposition of fat alone. – Ring. & Migr. 11: 113–115.


and Jukema, J. 1990. Budgeting the flight of a long-distance migrant: changes in nutrient reserve levels of Bar-tailed Godwits at successive spring staging sites. – Ardea 78: 315–337.

and Riersma, P. 1991. Temperate versus tropical wintering in the world’s northernmost breeder, the knot: metabolic scope and resource levels restrict subspecific options. – Acta XX Congr. Internat. Ornithol. (Orihuela); 761–772.

and Cadée, N. and Daan, S. 1995. Seasonality in basal metabolic rate and thermal conductance in a long-distance
migrant, the Knot (Calidris canutus). – J. Comp. Physiol. 165B: 37–45.

(Received 30 June 1995, revised 22 February 1996, accepted 13 March 1996)