
W. H. Karasov

Adaptation of nutrient transport during vertebrate evolution

13.1 Introduction

There are two basic kinds of questions physiologists ask about animal function (Mayr, 1961). One is how does something operate, and what is the mechanistic basis? The second kind of question is why did that mechanism come to be? Most physiologists receive their major training in the methods and problems of functional biology which is the domain of the first kind of question. ‘Why’ questions fall within the province of evolutionary biology which differs from functional biology in its methods and problems.

Presumably differences in nutrient transport within and between species reflect a particular animal’s adaptation to its caloric and nutritional needs. Adaptation can be considered as morphological or functional changes which favour normal life processes in a particular environment (Prosser, 1986). Not all organismal traits, however, have the requisite causal history to be adaptations (Brandon, 1985). In the eyes of some, biologists have not shown enough restraint in applying the term ‘adaptation’ to phenomena that they have studied. Gould & Lewontin (1979) point out that ‘plausible stories can always be told’, and most students of intestinal adaptation point to what they consider examples of this kind of abuse. New scientists in this field should be aware of the recent efforts aimed at adopting a more rigorous, methodological approach to comparative biology and the study of adaptation (e.g. Ridley, 1983; Brandon, 1985).

This chapter has three goals. The first is to analyse variation in nutrient absorption according to natural diet in order to illustrate some general considerations about adaptation and the evolution of characters. The second is to review some other patterns of
variation of intestinal nutrient transport, to define which represent adaptations, and the third is to highlight some interesting topics for future research.

13.2 Adaptation of nutrient transport according to diet

13.2.1 A starting hypothesis

It is useful to use deductive reasoning in order to predict what pattern of adaptation might be expected. A problem with an *a posteriori* approach is the aforementioned tendency to imagine adaptations where they do not exist (e.g. the Panglossian fallacy, Gould & Lewontin, 1979). Also, another problem with an inductive approach is that it often confuses correlations with cause-effect relationships (Calow & Townsend, 1981).

One might predict *a priori* that for dietary substances that yield energy but are not nutritionally essential there will be a positive relationship between their level in the natural diet and their rate of absorption by the intestine. Prime examples are likely to be the effect of dietary carbohydrate on glucose transport and possibly of dietary protein on the transport of non-essential amino acids. There are at least two arguments for expecting this relationship. The first is essentially an optimisation argument based upon the assumption that natural selection acts to maximise the acquisition of metabolisable energy. If the relationship between dietary level of an energy-containing substrate and its intestinal transport did not exist then: (1) valuable food calories might be wasted in excreta when feeding on diets with high substrate levels; and/or (2) the metabolic expenses of synthesising and maintaining the molecular machinery to absorb the substrate would be wasted when feeding diets containing very low levels of substrate. The second argument is based on the observation that ingestion of large amounts of a substrate without the ability to digest and absorb it can lead to life-threatening diarrhoea resulting from the solute’s osmotic effect in the intestine. As an example, sea-lion pups reportedly developed severe fermentive diarrhoea and died in five days when fed lactose and sucrose substrates for which they have no hydrolytic enzymes (Sunshine & Kretchmer, 1964).

In order to test the hypothetical relationship between diet and nutrient transport we need to be sure that, in the taxa from which we draw our study species, the mechanisms to transport glucose and amino acids are present for natural selection to act upon and thereby modulate transport activity. In the case of glucose and amino acid transport we can be reasonably confident that this is the case because Na⁺-dependent uptake processes have been identified in the intestine of vertebrates from every class (reviewed in Karasov, 1988). This is not the case for all solutes however. Carrier-mediated transport of ascorbic acid across the brush border, for example, is absent in many species and may be present only in those species which have a dietary requirement for ascorbic acid.

13.2.2 Relationship between dietary carbohydrate and sugar transport among species

Several studies have suggested that intestinal nutrient absorption varies interspecifically according to dietary levels of substrates. As an example, Buddington (1987) and Buddington *et al.* (1987) measured sugar and amino acid uptake at the intestinal brush border in five species of carnivorous fish which feed naturally on high-protein, nearly carbohydrate-free, foods and five species of omnivorous or herbivorous fish which feed on carbohydrate-containing foods. Proline uptake (per cm² nominal surface area) proved similar among the ten species, but glucose uptake in the herbivores and omnivores averaged almost four times higher than in the carnivores (*p* < 0.05).

An alternate and useful measure for making this kind of comparison is the ‘G/P ratio’, defined as the intestine’s summed uptake capacity for glucose divided by that for proline. Summed uptake capacity means the rate of absorption at a substrate concentration sufficient to saturate the transporters and summed over the whole length of the intestine. A virtue of this ratio is that it bypasses entirely the issue of to what measure of intestinal tissue the nutrient uptake rates should be normalised (e.g. to cm length, cm² area, mass, or protein content) when making comparisons between species. Figure 13.1 shows that the G/P ratios of 42 vertebrate species fit the same trend as the ten-species fish comparison. The ratio is significantly higher for herbivore/omnivores than for carnivores: respectively, 1.08 ± 0.22 (SEM; *n* = 25 species) vs 0.27 ± 0.05, (n = 17 species); *p* < 0.001 by one-tailed *t*-test. These species differences mainly reflect a lower glucose uptake per unit intestinal tissue in carnivores. Species differences
in glucose uptake per unit intestine in turn largely reflect species differences in the number of copies of the glucose transporter, as measured by kinetic analysis of binding studies (Ferraris et al., 1988).

In almost no case can the comparison of P/G ratios be made between closely related species having different dietary habits. Within reptiles, for example, the two carnivores are snakes (order Squamata, family Colubridae; average P/G ratio = 0.31) while two of the three herbivore/omnivores are lizards (order Squamata, family Iguanidae; mean P/G ratio = 1.42) and the other is a turtle (order Testudinata, family Testudinidae, P/G ratio = 0.57). It is conceivable that the low G/P ratio of snakes reflects some other unidentified aspect of ‘snakiness’ rather than their carnivorous diet. According to Ridley (1983) the best solution to this problem is to test the hypothesis many times independently. In this regard, it is reassuring that the trend of higher G/P ratio in herbivore/omnivores than carnivores holds true within each vertebrate class (with the exception of the amphibians which are all carnivores as adults).

There is another consideration related to this. Species were chosen and a statistical test was applied which assumed independence in testing the above hypothesis. Yet a third of the carnivorous species used were amphibians, an entirely carnivorous/insectivorous class in which the feeding habit may have evolved prior to speciation. Thus, the statistical comparison might have been biased. Ridley (1983) suggested a very conservative approach which might be used in this analysis: when counting cases of independent evolution, the units in the test can be a mixture of taxonomic levels (i.e. families, orders, or even classes), each of which is fairly uniform in regard to the measurement variable (in this case, diet or G/P ratio). For example, a single mean G/P ratio would be used for all amphibia and a single mean ratio for the two species of snakes. Using this procedure the sample sizes and hence degrees of freedom are smaller but the difference between carnivores and herbivore/omnivores is still significant ($p < 0.05$). If future taxonomic surveys of relationships between diet and nutrient transport are performed within an order, family, or genus then one can avoid the inherent ambiguity of drawing evolutionary conclusions from non-phylogenetically based analyses.

13.2.3 The roles of environment, genetics and development
The determinants of the pattern of adaptation depicted in Figure 13.1 could be any of three kinds: (1) genetically specified; (2) environmentally induced; and (3) developmental (Prosser 1986) – (2) and (3) are possible only within genetically fixed limits. Evidence exists for all three kinds of determinants in the case of regulation of sugar and amino acid transport by dietary carbohydrate and protein content.

Environmentally-induced adaptation to dietary composition has been studied most extensively in laboratory rodents. For example, in rats and mice intestinal monosaccharide absorption, whether measured in vivo or in vitro, increases monotonically with
dietary carbohydrate content (reviewed by Karasov, 1988; see also Chapter 5). The changes in glucose transporter activity in mice have been shown to be due to changes in the number of functional copies of the transporter (Ferraris & Diamond, 1986). Not all species are capable of such phenotypic adaptation. Glucose transport was not induced by increased dietary carbohydrate in carnivorous rainbow trout, frogs and the domestic cat (R. Buddington and J. Chen, personal communication) and in omnivorous American robins (D. Levey and W. Karasov, unpublished observations).

Phenotypic change in transport according to diet occurs for other nutrients. When laboratory rodents are fed high-protein rations, for example, amino acid absorption rates are enhanced (for review see Karasov et al., 1987). Unlike the case for regulation of glucose transport, however, the transport of many amino acids is not down-regulated at low dietary levels of protein. In mice, transport rates of essential amino acids were unaltered and possibly increased slightly when the mice were nitrogen deficient. For other essential nutrients such as minerals (iron, calcium phosphate) and vitamins (thiamine, Vitamin C) this pattern of maintained or enhanced transport during deficiency also appears to apply (Diamond & Karasov, 1987). All of these phenotypic changes seem to be compatible with the definition of adaptation.

A test for possible genotypic regulation of nutrient transport would be to feed carnivores and herbivore/omnivores the same diet and then measure nutrient transport. Buddington et al. (1987) achieved this for three carnivorous, two omnivorous, and four herbivorous fish using a ration with 45% protein and 25% digestible carbohydrate. The result (Figure 13.2) was that the G/P ratio decreased from herbivore/omnivores to carnivores, just as it did for the species in Figure 13.1. Because any contribution of phenotypic regulation to species differences in transport activity was eliminated, presumably the remaining differences are genetically fixed.

Many species undergo developmental changes in diet and in at least one case nutrient transport changes in parallel according to a genetically fixed schedule. Monkeyface prickletails (*Cebridichthys violaceus*) undergo a transition from carnivory to herbivory in the wild during development. In the laboratory when they were fed

---

**Fig. 13.2** The intestine's summed uptake capacity for glucose divided by that for proline (ordinate), as a function of the percentage of protein in the natural diet (abscissa), for eight species of fish: ○, carnivores; □, omnivores; ▲, herbivores; ● and ▲, a species (monkeyface prickletail) that is carnivorous while small (●) but is herbivorous when large (▲). Note that the ratio of glucose to proline uptake decreases with the proportion of protein in the natural diet, even though all eight species were studied while eating the same artificial diet. (After Buddington et al., 1987.)

the same carbohydrate-containing ration throughout development, small fish had relatively low glucose uptake rates typical of carnivores, whereas large fish had higher glucose uptake rates (Buddington et al., 1987). Thus, glucose transport was adaptively regulated according to a genetically fixed schedule.

13.2.4 Can adaptation of organismal traits be studied in isolation? Nutrient absorption is just one step in the digestive process and this has several implications for the study of its variation within and between species in the context of adaptation and evolution.
For example, adaptation of transport might be constrained by other components of the process. Hummingbirds have the highest glucose transport activity of any vertebrate studied so far, but the speed at which they can digest sucrose solutions may still be constrained by the time it takes to absorb glucose (Karasov et al., 1986). Why don’t they evolve even more glucose transporters? Perhaps the answer has to do with limitations on either total surface area of the gut or the density of carriers per unit membrane. As another example, a variation in transport rate might actually be inconsequential (therefore questionably ‘adaptive’) if compensatory adjustments in some other steps nullify its effect or if transport is not the rate-limiting step in the digestive process. In the case of adaptation of glucose transport to dietary carbohydrate level, however, there is some evidence indicating that transport is sometimes the limiting step in carbohydrate digestion and that other steps of the digestive process adapt in a parallel and not contradictory fashion to changes in dietary carbohydrate level (Karasov & Diamond, 1987).

13.3 Other patterns of variation in intestinal nutrient transport

13.3.1 Variation in transport activity with increased food intake

Increased energy and nutrient requirements might be expected a priori to require increased absorption of all nutrients. Endothermic mammals have nutrient requirements which exceed those of reptiles and fish by an order of magnitude. Summed intestinal uptake of nutrients in mammals exceeds that in reptiles and fish, by four and 13 times respectively (p < 0.001; Figure 13.3). The most important difference between these taxa, accounting for the higher summed uptake in mammals, is that small intestine surface area averages about four times greater in mammals than in reptiles and fish (Karasov, 1987).

Increased nutrient requirements and food intake also occur under several ontogenetic conditions such as reproduction and cold stress (in mammals). In these cases also, the intestine meets the increased requirement for all nutrients by an anatomic response: hyperplasia of the intestinal mucosa (reviewed in Karasov & Diamond, 1983).

The response of the gut to increased food intake involves numerous changes in structure and function which have the net

Fig. 13.3 Relationships between the sum of glucose and proline uptake capacities and body mass in fish (□), reptiles (○) and mammals (numbers without symbols). The regression lines do not differ significantly in slope. Based on a comparison of the intercepts at unity, the uptake capacity of mammalian intestine for sugar and amino acids exceeds that of reptiles and fish by 3.7 and 12.6 times, respectively. Incubation temperatures were 20°C for fish and 37°C for reptiles and mammals. (Taken with permission from Karasov, 1987.)

effect of maintaining extraction efficiency relatively constant in the face of much greater nutrient flux through the gastrointestinal tract. This might be a good system in which to study adaptation of a whole suite of organismal traits (gut morphology, digesta transit time, digestive enzymes and nutrient transporters) rather than a single step of the digestive process alone.
13.3.2 Variation in transport activity with temperature and salinity

There have been relatively few studies of the effects of changes in these environmental parameters on intestinal nutrient absorption. Changes in salinity have relevance primarily for fish, while changes in temperature potentially have physiological significance for all members of all vertebrate taxa. Acclimation of fish both to different temperatures and salinities has been reported to alter nutrient absorption rates (reviewed in Karasov, 1988). Changes in temperature and salinity also cause changes in intestinal membrane fluidity in some species (Smith & Kemp, 1971; Leray et al., 1984) and this could affect passive permeability to nutrients or their carrier-mediated transport (by affecting translocation rates of nutrient–carrier complexes). The physiological significance of the changes in nutrient absorption or membrane fluidity have not yet been fully explained. It is conceivable that the changes in the former are simply consequences of changes in the latter and that altered nutrient absorption rates do not relate to any 'need' to improve nutrient absorption. Thus, this could be an interesting system in which to study variation in an organisinal trait (nutrient transport) which occurs out of physical necessity and is thus not really an 'adaptation' at all. What is further appealing about this system is that the requisite methods for studying it are available: techniques for preparing membrane vesicles and measuring membrane fluidity and solute transport, and even altering membrane fluidity in vesicles experimentally using compounds added during vesicle preparation.

13.4 Concluding remarks

Most of the present discussion has focussed on the current best example for evaluating adaptation of intestinal nutrient transport within an evolutionary context. For the case of regulation of glucose transport there was an a priori expectation about how it should vary with dietary carbohydrate level, and several independent tests of the hypothesis showing that in four vertebrate taxa (classes) there was a higher mean G/P ratio among species which naturally ingest significant amounts of carbohydrate. The analysis will be further strengthened if future studies are phylogenetically based in this manner. Evidence exists for all three kinds of determinants (genetics, environment and development) for the adaptive pattern shown in Figure 13.1.

Other patterns of variation in intestinal nutrient absorption within and between species offer interesting opportunities for studying adaptation. Nutrient absorption rates are adapted both phenotypically and genotypically to increased food intake, as might be predicted a priori. The response of the gut to altered food intake may be an interesting system for studying the adaptation and evolution of several steps of the digestive process in an integrated fashion. Not all organismal traits are necessarily adaptations. Some instances of variation in nutrient transport in response to changes in salinity or temperature may be an example of this.

Acknowledgements

I thank Drs R. K. Buddington, R. P. Ferraris and J. M. Diamond for sharing with me their unpublished manuscripts.

References


Gould, S. J. & Lewontin, R. C. (1979). The spandrels of San Marco and
physiological responses. 39B, 57-65.


