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Nutrition and metabolism: is a chicken just a pig with feathers?

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Abstract

Individuals of the same species may look the same, but they are genetically somewhat different. Different species may look different, but share many common features. The genetic difference between a chicken and a pig is roughly 25%, which may seem considerable. However, it often reflects genetic differences to ensure that the same function can be realized in a (somewhat) different way. As animal nutritionists, we often focus on the differences between species and ignore (or: take for granted) the commonalities. For example, arginine is an essential amino acid for birds but not for mammals because birds lack an enzyme to enter carbamoyl-phosphate into the urea cycle. However, birds possess the other steps of the urea cycle allowing them to synthesize arginine from citrulline, and to catabolize arginine to proline or glutamate. This single missing step causes birds to excess nitrogen via the uric acid cycle rather than via the urea cycle, as in mammals. Mammals also use the uric acid cycle to metabolize purines (e.g., adenine), which is a building block of DNA and the core of ATP. Both species thus use (parts of) both cycles. The cost of synthesizing and excreting excess nitrogen is approximately 40.3 kJ/g N for urea and 60.7 kJ/g N for uric acid. In both cases, 56% is retained in excretion product and 44% is lost as heat with implications for the protein value in energy systems. A better understanding of the metabolic commonalities between species may help us in appreciating the practical differences.

Résumé

Les individus d'une même espèce peuvent se ressembler, mais ils sont génétiquement un peu différents. Des espèces différentes peuvent avoir un aspect différent, mais partagent de nombreuses caractéristiques communes. La différence génétique entre un poulet et un porc est d'environ 25 %, ce qui peut sembler considérable. Cependant, des différences génétiques accomplissent souvent la même fonction, mais d'une manière (un peu) différente. En tant qu'experts de la nutrition animale, nous nous concentrons souvent sur les différences entre les espèces et ignorons (ou considérons comme acquis) les points communs. Par exemple, l'arginine est un acide aminé essentiel pour les oiseaux, mais pas pour les mammifères, car les oiseaux sont privés d'une enzyme permettant d'introduire le carbamoyl-phosphate dans le cycle de l'urée. Cependant, les oiseaux ont ce qu'il faut pour activer les autres étapes du cycle de l'urée, ce qui leur permet de synthétiser l'arginine à partir de la citrulline et de cataboliser l'arginine en proline ou en glutamate. Cette seule étape manquante fait que les oiseaux évacuent l'azote par le cycle de l'acide urique plutôt que par le cycle de l'urée, comme c'est le cas chez les mammifères. Les mammifères utilisent également le cycle de l'acide urique pour métaboliser les purines (par exemple, l'adénine), qui sont un élément constitutif de l'ADN et un composant clé de l'ATP. Les deux espèces utilisent donc (en partie) les deux cycles. Le coût de la synthèse et de l'excrétion de l'azote excédentaire est d'environ 40,3 kJ/g N pour l'urée et de 60,7 kJ/g N pour l'acide urique. Dans les deux cas, 56 % sont retenus dans les produits d'excrétion et 44 % sont perdus sous forme de chaleur, ce qui a des répercussions sur la valeur protéique considérée dans les systèmes énergétiques. Une meilleure compréhension des points communs métaboliques entre les espèces peut nous aider à reconnaître les différences pratiques.

Introduction

Increasing the efficiency of protein utilization is an important issue in livestock for production. Apart from the cost of protein (the input side), the issue is also driven to reduce nitrogen excretion (the output side) to limit the environmental impact of livestock production. The quantitatively most important role of dietary protein is to provide the amino acids for animal-derived products, such as meat, milk, and eggs. The similarities in the amino acids composition of these products is not surprising because, to some extent, they serve the same biological purpose. Meat originates from muscle, but milk is provided by the mother to the young to grow (muscle). Similarly, the amino acids in egg yolk and egg white are there to be used by the embryo to develop (muscle).

The amino acid composition of plant proteins can differ from what the animal needs, and the amino-group of amino acids that are not incorporated in animal protein will be removed and the carbon chain can be used for other purposes. Some of these amino-groups can be used to synthesize non-essential amino acids, but the remainder will be excreted by the animal as ammonia (fish), urea (mammals), or uric acids (birds). At least 30% of the nitrogen of dietary protein will be excreted by the animal.

The nitrogen that is lost also represents an energy loss for the animal. The gross energy values for ammonia, urea, and uric acid are 91.5, 75.9, and 114.7 kcal/g N, respectively, and this energy loss is accounted for in the metabolizable energy value of the diet (van Milgen, 2021). While it does not require additional energy to make ammonia, it is often ignored that energy is required to synthesize urea and uric acid. Part of that energy is retained in the excretion product (and thus accounted for in the ME value), but part of it is lost as heat. The latter is part of the heat increment and thus part of the NE value of protein.

The urea "cycle" in mammals and birds

Hans Krebs (1900-1981) is well-known for the discovery of the so-called Krebs or TCA cycle to produce ATP from acetyl-Co. Is it much less known that Krebs also contributed to the discovery of the urea and uric acid cycles. Consequently (and to look smart), if someone says "It is used in the Krebs cycle", respond by saying "which Krebs cycle?".

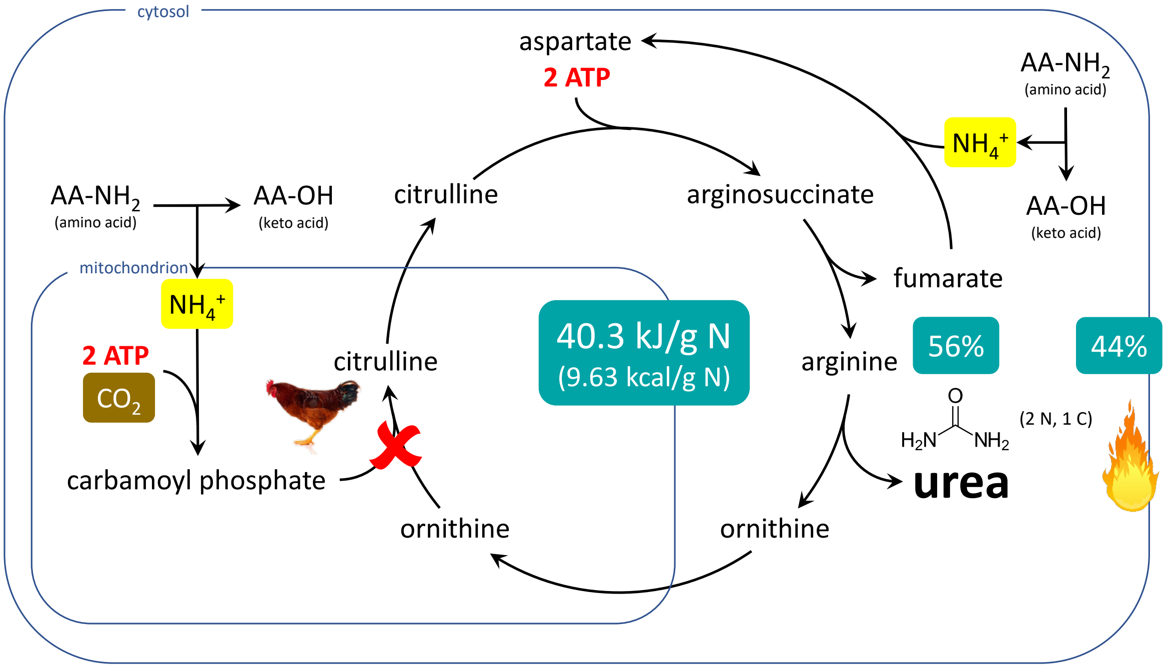

Figure 1. The urea cycle: urea (the output) contains two nitrogen and one carbon atom, which are input by the metabolites with a yellow and brown background, respectively. Its costs 9.63 kcal/g N to synthesize urea, 56% of which is retained in the product and 44% is released as heat. Birds cannot synthesize carbamoyl phosphate, but they possess the other reactions of the urea cycle.

Urea is a relatively small molecule and contains two nitrogen and one carbon atom (Figure 1). One nitrogen and the carbon enter the cycle as carbamoyl-phosphate. The other nitrogen enters the cycle as aspartate the carbon of which leaves the cycle as fumarate (which can be used to resynthesize aspartate by accepting an amino group from another amino acid given in excess).
Arginine is an intermediate metabolite in the urea cycle. Birds cannot synthesize arginine because they lack the enzyme to synthesize carbamoyl-phosphate. They therefore have a dietary requirement for arginine. Because muscle protein contains approximately equal quantities of lysine and arginine, the recommended level of arginine, relative to lysine, is around 100% in birds, while it is around 42% in pigs (because pigs can make arginine).
Although one can say that "birds not have a urea cycle", this does not mean that they do not use certain elements of the urea cycle. They lack only one reaction (the enzyme to synthesize carbamoyl-phosphate) of the cycle, but they can use all other reactions including the synthesis of arginine from citrulline The word "citrulline" is derived from the Latin word for watermelon. From the experience I have with my backyard chickens (n=2), I can tell you that they love watermelon and its rind. Citrulline is also synthesized when arginine is used to synthesize nitric oxide, a vasodilator, and this citrulline can be used to resynthesize arginine. It is thus not correct to say that birds "cannot synthesize arginine", because they do (from citrulline), but they do not possess the complete urea cycle.

The uric acid "cycle" in mammals and birds

Birds and reptiles excrete nitrogen via the uric acid cycle, which is shown in Figure 2. Uric acid contains four nitrogen and five carbon atoms. Two nitrogen atoms enter the cycle as glutamine, one as aspartate (like in the urea cycle), and one nitrogen comes in from glycine. Glycine also provides two of the five carbon atoms, and the three remaining carbon atoms originate from CO_2 and N^{10}-formyl-THF. The latter is a so-called one-carbon metabolite linked to tetrahydrofolate, derived from folic acid (vitamin B9).

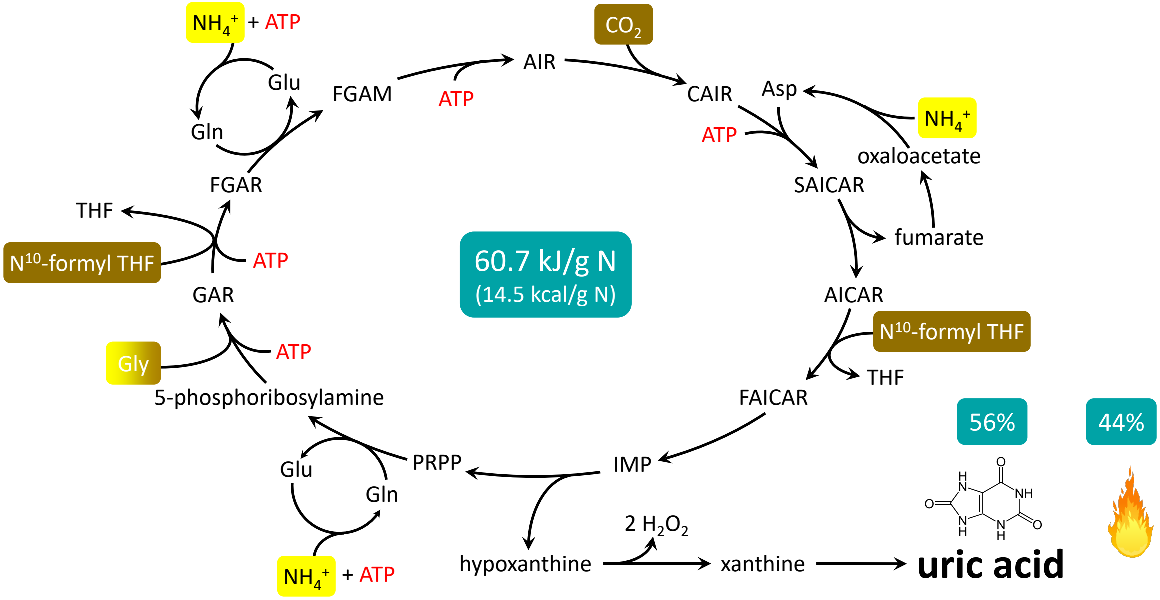

Figure 2. The uric acid cycle: uric acid (the output) contains four nitrogen and five carbon atoms, which are input by the metabolites with a yellow and brown background, respectively. Its costs 14.5 kcal/g N to synthesize urea, 56% of which is retained in the product and 44% is released as heat. Mammals also use (part of) the uric acid cycle to synthesize purine (i.e., AMP and GMP) from IMP (inosine monophosphate).

Hydroxyxanthine is the output of the uric acid cycle, which can be metabolized further to uric acid. It costs 14.5 kcal/g N to synthesize uric acid, 56% of which is retained in uric acid and 44% is released as heat (van Milgen, 2021).

Although poultry nutritionists acknowledge that glycine is required for uric acid synthesis, the fact that two of the five carbons come from N^{10}-formyl-THF is frequently ignored. However, part of the energy retained in uric acid originates from N^{10}-formyl-THF. The metabolism of 1-carbon metabolites is receiving more attention (e.g., in cancer research). Methionine is an important 1-carbon carrier in methylation reactions (e.g., to methylate Arg and Lys in histones and in epigenetics). Although methionine is a 1-carbon carrier, it is not necessarily the dietary source of 1-carbon. One-carbon originates from the catabolism of betaine (and thus from choline), tryptophan, and histidine. It also originates from methionine when methionine is used for cysteine synthesis (e.g., for the synthesis of feathers). Serine and glycine are also involved in the synthesis of 1-carbon metabolites and constitute the main route of 1-carbon synthesis and metabolism.

Although mammals do not use the uric acid cycle to excrete excess nitrogen from protein, they use almost all of the uric acid cycle for other, critically essential processes. IMP (inosine monophosphate) is the precursor of the purines AMP and GMP, and thus for ATP and GTP. These purines are also the backbone of DNA and RNA. It is thus not too difficult to see the importance of the uric acid "cycle" for all organisms, and also illustrates the importance of glycine and 1-carbon metabolism. To synthesize IMP, PRPP (phosphoribosyl pyrophosphate) is required, which can be synthesized from glucose. Although the animal possesses mechanisms to efficiently "recycle" the purines and pyrimidines, they are also catabolized resulting in excretion products uric acid and allantoin.

These examples show that both mammals and bird possess (almost) all of the reactions of the urea and uric acid cycle, but that small differences can result important physiological differences to excrete nitrogen from excess dietary protein. As animal nutritionists, it is equally important to see and manage these differences as it is to see the commonalties.

References

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