IS INTESTINAL ABSORPTION CAPACITY RATE-LIMITING FOR PERFORMANCE IN POULTRY? 1,2

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SUMMARY

In recent years, there has been a growing perception that limitations in gastrointestinal absorption may be detrimental to posthatch survival and subsequent performance. This perception is based on a large body of information demonstrating that genetic selection for growth in domestic poultry alters intestinal structure from that of their wild counterparts. Furthermore, recent advances in our understanding of the energetic costs of absorption suggest that biochemical as well as structural changes in intestinal function have decreased absorptive function and efficiency in both chickens and turkeys. The recent discovery that some gastrointestinal peptides enhance nutrient absorption has allowed limited, direct testing of this hypothesis. The results of preliminary studies indicate that intestinal absorption enhancement technology may have beneficial practical application. More detailed studies are needed to fully assess the economic potential of intestinal absorption enhancement in poultry.

Key words: Gastrointestinal peptides, genetic selection, intestinal absorption

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DESCRIPTION OF PROBLEM

There is a perception among poultry nutritionists that the absorption of nutrients is a potential rate-limiting factor in survival, growth, and feed conversion in hatchlings as well as in growing birds, and this has been proposed to be an important emerging issue in the poultry and livestock industries (see reviews [1, 2]). For poultry, this perception has been fostered by the emergence of ideas concerning the development and function of the digestive tract that have been developed over the last two decades. They are: 1) growth during the early posthatch period places a priority on the development of "supply organs," such as the digestive tract, in order to assure later growth of "demand tissues," such as muscle [3, 4]; 2) genetic selection for growth and reproduction has altered the digestive tract of poultry to such a degree that digestive processes are not fully developed at hatch [5, 6, 7]; and 3) the gastrointestinal tract accounts for a large share of the bird's total energy needs, and genetic selection for production traits may not have resulted in concomitant selection for perfectly correlated enhanced gastrointestinal tract function and energetic efficiency [8, 9, 10]. Collectively, these concepts imply that an insufficient capacity of the intestinal tract for nutrient absorption could negatively affect performance and survival [3, 8, 11]. Similarly, potential energetic inefficiencies in the gut tissues could limit phenotypic expression in birds with superior genotypes [2]. Although our assumption, based on current data, is that absorptive capacity is rate-limiting, alternative interpretations of existing information support the premise that the gut has achieved perfect balance with post-absorptive tissue metabolism [12, 13].

Recent work has been directed at achieving a better understanding of factors that affect nutrient absorption and the development of potential therapeutic techniques to remedy possible limitations in nutrient absorption. This paper will briefly review the rationale related to current perceptions about intestinal development and function as a rate-limiting process for poultry production and discuss new technologies that are available to address these problems.

THE IMPORTANCE OF EARLY GASTROINTESTINAL GROWTH

Previous studies have shown that at posthatch, the gastrointestinal tract of the hatchling chick or goose accounts for a larger percentage of whole body weight [3, 4] than in adult birds. This percentage steadily decreases with age. Similar findings have been reported for the domestic turkey [9, 10] (Figure 1). This developmental pattern is believed to reflect a survival strategy in which great importance is placed on the development of nutrient supply functions early in life in order that post-absorptive growth functions can be maximized later in the life cycle [14]. During early life, the bird can afford to partition only a limited quantity of nutrients and energy for tissue growth, which must be distributed among different organ systems. Because supply organs are responsible for making energy available for post-absorptive growth processes and because growth ceases when the energy supply from the supply organs is less than the maintenance supply of the demand organs, the bird places a high priority on early intestinal growth and development. It has been suggested that final growth in the bird is directly proportional to an early high specific growth rate of supply organs [4]. Dror et al. [11] have concluded that development of the duodenum and jejunum may be limiting for growth in young birds of heavy breeds. This agrees with earlier work by Pinchasev et al. [15], who concluded that "the GIT is more limiting in heavy- than in light-breed chicks."

MODERN GENETIC SELECTION HAS ALTERED THE INTESTINAL TRACT

Genetic selection for production parameters has altered both the form and the function of the intestinal tract in poultry. Dror et al. [11] found that the relative weight of the duodenum and jejunum was greater in a light breed of chickens than in a breed selected for increased body weight. Similar differences were noted by Nir et al. [16] between light-breed and heavy-breed chicks. Nitsan et al. [8] reported that cockerels from a line selected for high 8-wk body weight had smaller intestinal tracts relative to body weight at hatch than did a
non-selected parent line. This difference disappeared after Day 8 posthatch. Cherry et al. [17] reported that broiler chickens selected for high body weights tended to have smaller gastrointestinal tracts relative to body weight than those selected for low body weight or White Leghorns.

Comparisons of the digestive tracts of wild turkeys and those of genetically selected modern turkeys give insight into the magnitude of the changes that result from modern genetic selection. Studies comparing the digestive tracts of wild and modern domestic turkey hatchlings demonstrate that wild turkeys have a longer (intestinal length/unit body weight) and less dense (weight/unit length) intestinal tract than domestic lines of turkeys that had been selected for 16-wk body weight or 180-day egg production [18] (Figure 2). Additionally, the intestinal mucosa constitutes a smaller percentage of wet and dry intestinal weights of wild turkeys at hatch [19] (Figure 3). Similar values for intestinal mucosal percentages have been reported by Jackson and Diamond [20] for the wild Red Jungle Fowl (Gallus gallus). It is likely that these differences reflect an adaptation to domestication and genetic selection. Wild turkeys need to maintain a longer intestinal tract in order to supply a template for quick upregulation of absorptive processes when nutrient supplies are abundant; however, they cannot afford to maintain a large quantity of energetically expensive absorptive epithelium. In contrast, domestic turkeys can afford to develop a shorter, more dense intestinal tract with a higher percentage of absorptive mucosa because they are provided with a constant supply of nutrients. Similar findings were reported by Coles [21] in a comparison of wild turkeys with Hybrid and Egg line turkeys.

Not only intestinal size but digestive enzyme activity has changed with genetic selection for production parameters. Nir et al. [16] reported that the total activity of pancreatic amylase and chymotrypsin were significantly increased in light-breed chicks as compared to heavy-breed chicks in response to overfeeding. They postulated that this could be a limiting factor in the ability of heavy-breed chicks to digest excessive amounts of food. Nitsan et al. [8] and Nir et al. [5] have suggested that secretion of digestive enzymes could be a limiting factor in food intake, digestion, and subsequent growth in broiler chicks. O'Sullivan et al. [22] reported that turkey poult's from lines selected for high 56-day body weights had higher pancreatic enzyme levels than lighter lines when compared at a common age. However, when comparisons were made at a common body weight (80±5 g), these differences disappeared, suggesting that feed
intake was mediating these digestive enzyme levels. Pinchasov and Noy [23] found that turkey poults have a slightly limited capacity to digest starch during the first 2 to 4 days posthatch, but develop an adequate capacity thereafter. Similarly, Sell et al. [24] found that 2-day-old poults have appreciable intestinal maltase- and isomaltase-specific activities. Coles [21] demonstrated that the wild turkey has higher disaccharidase-specific activities in the small intestine at hatch than Hybrid line turkeys.

These studies suggest that genetic selection has affected digestive and absorptive function, especially in newly hatched chicks or poults, and that these effects may have important implications for poultry production systems. As growth rate increases and market age decreases, the percentage of time the animal spends as a neonate increases. This places increased importance on early digestive and absorptive events that occur immediately posthatch. It also points toward the possible need for dietary intervention and management practices at an early age in order to ensure maximal performance.

**The Importance of the Energetic Costs of Intestinal Absorption**

The gastrointestinal tract can account for as much as 20% of the total energy needs of cattle [25]. Park [26] reported that the gastrointestinal tracts of chickens can account for as much as 15–25% of whole bird energy requirements. A recent review by Cant et al. [27], in which the energy requirements of the gastrointestinal tract were modeled, suggests that if an animal used any more than this to support gastrointestinal function, the overall
utilization of energy for growth would be greatly decreased. Hence, it appears that this range is a biological constant for higher vertebrates.

A detailed analysis of the energy requirements of intestinal tissues of 2-wk-old turkey poults reveals that 50-60% of the intestinal tissue requirements are expended in the one-celled layer of absorptive mucosa [9]. Of the energy expended by the mucosa, 30% can be accounted for by the Na+/K+ ATPase, located on the basolateral membrane of the enterocytes. This enzyme maintains the Na+ gradient necessary for support of the intestinal transport of glucose, amino acids, and other nutrients [28]. Park [26] has reported a similar value for the percentage of energy used by the Na+/K+ ATPase in chicks. It is obvious from these figures that gastrointestinal function and nutrient absorption are important regardless of the energetic costs these processes impose upon the animal.

Mitchell and Smith [29] were the first to associate a decrease in small intestine length, wet weight, and absorptive mucosal mass, resulting from genetic selection in chickens for enhanced growth, with increased overall energetic efficiency. They postulated that the decrease in intestinal absorptive mucosal mass resulted in more efficient functioning of the small intestine since the intestinal mucosa accounts for a major portion of the energy expenditure in the gut. Diamond [30] found a two-fold redundancy in the intestinal absorptive capacity for glucose and dietary glucose intake in the rat, rabbit, cat, chicken, and mouse. Obst and Diamond [31], however, speculated that the modern chicken may not have the intestinal glucose absorptive capacity to meet its metabolic needs (Figure 4).

Jackson and Diamond [20] found that there was no redundancy in the ability of the Red Jungle Fowl to ingest glucose and its ability to absorb glucose. These authors have suggested that red jungle fowl, because they evolved in an environment where nutrient availability was sporadic, cannot afford to maintain a constant high level of absorptive capacity. They speculated that in times of high nutrient availability, they are capable of quick upregulation of absorptive function in their intestinal tract.

This is not the only biological model in which intestinal glucose absorption appears to be rate-limiting for postabsorptive processes. Weiss et al. [32] have recently demonstrated that both intestinal disaccharidase activity and intestinal glucose absorption are rate-limiting for lactation in the growing rat. In contrast, Nir et al. [12] found that chicks force-fed feed exceeding the amount consumed voluntarily, developed a remarkable capacity to digest and absorb food. Similarly, Jorgensen et al. [13] concluded that genetic selection favoring broilers with efficient feed conversion ratio (FCR) inherently excludes birds eating more than their digestive capacity.

Although Mitchell and Smith [29] alluded to changes in the "efficiency of absorption" due to genetic selection in chickens, it was Bird et al. [33] who first attempted to quantitatively define the efficiency of absorption in terms of energetic costs. These authors proposed a method of evaluating the energetic efficiency of glucose absorption in mice by constructing a scalar in which glucose uptake from the gut was expressed in comparison to total ATP expenditures by intestinal tissue (see review by Croom et al. [2] for a detailed discussion of this concept). This scalar was defined as the apparent energy efficiency (AEE) of glucose absorption. This method has been used to demonstrate changes in glucose absorption associated with age and peptide enhancement [28, 33] as well as for a partially trisomic genotype [34]. This scalar has been used to describe the energetic efficiency of intestinal glucose absorption in mice [33, 34, 35, 36] and turkey poults [10].

Croom and his associates were the first to evaluate the AEE of glucose absorption in animals selected for enhanced growth, feed efficiency (mice and turkey poults), or body composition (mice). Fan et al. [10] observed that turkey poults selected for enhanced
growth did not demonstrate any changes in the APEE of glucose transport (Figure 5). These findings pose an interesting paradox. Even though the poult selected for growth do not have an enhanced APEE for jejunal glucose uptake, the poult themselves have a better FCR and a greater body weight. Similar observations have been made in mice selected for growth [35]. Croom et al. [2] suggested two possible interpretations for these observations: 1) selection for increased efficiency of glucose absorption is concomitant with genetic selection for increased growth or feed efficiency; or 2) there is an uncoupling of genetic selection for the efficiency of growth and that of intestinal function. An enhancement of the energetic efficiency of glucose uptake or total glucose absorption should result in enhanced performance. These questions are exceedingly complex and are not easily resolved. Fortunately, recent advances in the development of technologies to increase intestinal absorption may allow resolution of these economically important questions.

**Gastrointestinal Peptide Enhancement of Nutrient Absorption**

Recent studies have demonstrated that the gastrointestinal peptides, epidermal growth factor (EGF), and peptide YY (PYY) enhance carbohydrate, amino acid, and fat absorption from the intestinal tract (see review by Bird et al. [28]). Schwartz and Storozuk [37] were the first to demonstrate that either systemic or intraluminal injections of EGF, a gastrointestinal growth factor with a primary structure of 56 amino acids, enhances galactose and glycine absorption from the intestines. Although these initial studies were conducted in rats, subsequent studies have shown that EGF enhances glucose, galactose, proline, glutamine, and water uptake from the small and large intestines of mice, rabbits, and turkeys [38, 39, 40, 41, 42, 43].

PYY is a member of the pancreatic polypeptide family of brain/gut peptides. It has a primary structure of 36 amino acids and is believed to be the primary humoral agent involved in the "ileal brake syndrome" as reviewed by Taylor [44]. This syndrome appears to be an intestinal regulatory mechanism by which the body corrects nutrient malabsorption. Administration of PYY has been reported to decrease not only pancreatic secretion but also gastric and intestinal motility. Bird et al. [28] were the first to report that PYY increases glucose absorption in mice injected subcutaneously with 300 μg/kg of body weight for 3 days. Of special interest was the observation that the increase in glucose absorption associated with PYY administration was not accompanied by an increase in APEE of glucose uptake (Figure 6). This suggests that PYY administration can affect the rate and efficiency of glucose absorption and may increase the efficiency of metabolizable energy utilization.

Especially intriguing are reports showing that gastrointestinal peptides can enhance intestinal nutrient absorption at hatching or birth when administered in ovo or in utero. Buchmiller et al. [45] reported that term rabbit fetuses administered EGF in utero via miniosmotic pumps had greater intestinal lactase and maltase activity as well as greater transport of glucose and proline. Similarly,
Goetzman et al. [46] reported enhanced intestinal enzyme content and increased glucose and glutamine transport in premature, neonate simians administered EGF in utero via miniosmotic pumps.

Peebles et al. [47, 48] have shown that enhancement in absorptive function by both EGF and PYY do not involve changes in yolk uptake from the yolk sac and stalk (Figure 7). Furthermore, they have noted that in ovo administration in broiler hatching eggs with PYY results in heavier hatchlings [41]. Coles et al. [40] demonstrated that administration of EGF or PYY in ovo at Day 25 of incubation to Nicholas turkey eggs increased the rate of glucose absorption by poults at hatch by 200-250% (Figure 8). No intestinal tissue oxygen consumption measurements were reported in this study. Park [XI, however, found that jejunal enterocytes isolated from young and adult chickens significantly decreased O$_2$ uptake after exposure to EGF in vitro. Additionally, the intracellular pH of enterocytes from adult birds was transiently reduced.

Coles et al. [41] administered either physiological saline (control) or PYY to broiler eggs at Day 18 of incubation. Growth and FCR were determined at 7, 21, and 42 days of age. Feed intake was recorded weekly. Broilers from PYY-treated eggs had greater growth and improved FCR during the first week posthatch (Figures 9 and 10). The authors speculated that the lack of effect on growth and FCR after Week 1 was due to the turnover of intestinal epithelial cells affected by PYY in ovo. Chick enterocytes turn over in approximately 48 hr [49]. It is likely that the failure to observe an effect on growth and FCR after 7 days was related to the replacement of enterocytes affected by PYY with newly differentiated enterocytes not having enhanced insertion of SGLT1 transporters from the intracellular pool into the luminal membrane. Consequently, PYY may have to be administered after hatching to ensure continuation of increases in growth and improved feed efficiency. Coles et al. [50] have recently tested the effects of combining in ovo and posthatch administration of PYY to broiler eggs and chicks on posthatch growth and FCR. The FCR for Weeks 2 to 3 improved for PYY-treated birds and average weight of PYY-treated birds exceeded that of controls by Week 6 [50].

Recently, Kocamis et al. [51] reported that in ovo administration of recombinant human insulin-like growth factor-1 to broiler chicken eggs during the first 4 days of incubation resulted in dramatic changes in growth and FCR as the result of increased posthatch skeletal muscle growth. It is interesting to note that Guillermo et al. [52] found increases in PYY gene expression to be associated with increases in growth hormone and insulin-like growth factor-1 in growth-hormone transgenic mice. Similarly, Bird et al. [53] found that repeated exogenous administration of recombinant bovine somatotropin to sheep increased the rate of glucose and proline absorption from the duodenum. The increases in growth and FCR observed by Kocamis et al. [51] may thus be due in part to a secondary effect of increased endogenous PYY on the intestines of the embryo and chick.
FIGURE 9. Effect of *in ovo* administration of saline or 600 μg/kg egg weight PYY to broiler eggs at Day 18 of incubation on broiler chick weights at 7 days of age. PYY was significantly different (P < .05) from saline control [40].

FIGURE 10. Effect of *in ovo* administration of saline or 600 μg/kg egg weight PYY to broiler eggs at Day 18 of incubation on chick feed conversion at 7 days of age. PYY was significantly different (P < .05) from saline control [40].
ABSORPTION ENHANCEMENT IN POULTRY: HYPE OR HELP?

To date, the case for intestinal nutrient absorption being rate-limiting in poultry production is based on limited, direct experimentation using intestinal absorption enhancing peptides and a large body of data suggesting that intestinal structure and function of modern meat-type poultry may not be adequate for maximum growth rate. However, when taken as a whole, these studies support the hypothesis that intensive genetic selection for growth in poultry has "uncoupled" intestinal nutrient delivery from increased post-absorption nutrient demand. This may have resulted from alterations in genetic correlations between intestinal absorption and post-absorptive synthetic process. The lack of correlation may apply not only to the rate and amount of nutrients absorbed from the digestive tract but also to the energetic cost of nutrient absorption. This is especially true of the production data presented above, which suggests that the concept may have sound practical merit.

CONCLUSIONS AND APPLICATIONS

1. Like any new technology, the application of absorption enhancement to practical production systems cannot be implemented until a number of key variables associated with its use can be more clearly defined. These include the influence of genotype, age, and physiological state on the dose and time of administration for maximizing intestinal absorption.
2. Additionally, the dose-response characteristics and duration of action of proabsorptive agents such as PYY need to be more fully understood, and the cost vs. return must be evaluated.
3. The understanding of variables such as these will help production specialists define if and when absorption enhancement will be beneficial.

REFERENCES AND NOTES


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