Advances in Animal Compensatory Growth Research: Postprint

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Abstract

Compensatory growth technology is widely employed during specific feeding stages of herbivores, poultry, and swine, conferring benefits such as enhanced body protein deposition rates, improved feed utilization efficiency, promoted hormone secretion, and increased enzymatic activity. This paper expounds upon the effects of compensatory growth on animal organisms and its limiting factors, and provides a brief overview of the current application status and future prospects of compensatory growth in animal production.

Full Text

Research Progress on Compensatory Growth in Animals

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Abstract: Compensatory growth is widely applied during specific feeding stages in herbivores, poultry, and swine to improve protein deposition rates, enhance feed utilization efficiency, promote hormone secretion, and increase enzymatic activity. This review elaborates on the effects of compensatory growth on animal physiology and its limiting factors, and discusses the current status and future prospects of compensatory growth applications in animal production.

Keywords: compensatory growth; feed restriction; animal production

Compensatory growth, also known as catch-up growth, refers to the phenomenon where higher animals exhibit accelerated growth rates after nutritional levels return to normal following early-stage malnutrition or deliberate feed restriction [1-2]. Based on growth outcomes, compensatory effects can be categorized into five gradients: hyper-compensatory, full compensatory, partial compensatory, zero compensatory, and negative compensatory growth [3]. Compensatory growth is influenced by multiple factors, including sex, feed intake, restriction intensity, and initiation timing. In recent years, research on compensatory growth has gradually shifted from apparent performance indicators such as growth performance, immune function, and digestive enzyme activity toward molecular regulatory mechanisms. Deeper factors related to compensatory growth mechanisms, such as hormonal regulation and related gene expression, have been gradually elucidated, providing a more comprehensive theoretical foundation for its application in animal production practice.

1. Factors Affecting Compensatory Growth

1.1 Sex

Numerous experimental results demonstrate that sex is an important factor affecting compensatory growth in animals. Shariatmadari et al. [4] restricted feed in broiler chickens from 7 to 14 days of age and then allowed compensatory growth until 49 days, finding that final body weight, feed efficiency, and growth rate were significantly higher in males than in females ($P<0.05$), with male abdominal fat weight significantly lower than that of females ($P<0.05$). Whitaker et al. [5] conducted protein restriction experiments on female rats, showing that male offspring exhibited significantly higher weight gain rates than female offspring ($P<0.05$), along with superior performance in feed intake, activity levels, and metabolic rate. Bhasin et al. [6] reported that male offspring from feed-restricted mice showed better glucose tolerance, which may explain their higher weight gain rates. These findings indicate that male animals may have better compensatory growth capacity than females, and that separate feed restriction and compensatory growth protocols for males and females could achieve better results.

1.2 Feed Restriction Intensity

Feed restriction typically occurs during the juvenile period when animals are not yet fully developed, and excessive restriction can impair subsequent compensatory capacity. Cao Yujuan [7] conducted energy restriction at 5%, 10%, and 15% levels in Yangzhou goslings from 19 to 28 days of age, followed by compensatory growth until 70 days. The results showed that the 5% and 10% restriction groups had no significant differences in body weight compared with the control group ($P>0.05$), while the 15% restriction group was significantly lower than the control group ($P<0.01$). Lippens et al. [8] restricted broiler chickens by 20% and 10% energy from 4 to 8 days of age; after compensatory growth, the 10% restriction group achieved body weight comparable to the control group (P>0.05), whereas the 20% restriction group failed to achieve effective compensatory growth due to excessive restriction. Furthermore, Zhang Chongzhi et al. [9] reported that severely restricted Mongolian lambs [metabolizable energy (ME): 8.61 MJ/kg, crude protein (CP): 5.70%] had significantly smaller average muscle fiber areas in the longissimus dorsi, semitendinosus, and biceps brachii muscles compared with the control group (ME: 10.88 MJ/kg, CP: 15%) (P<0.05), and were extremely significantly lower than the moderate restriction groups (ME: 10.88 MJ/kg, CP: 10.00%; ME: 9.41 MJ/kg, CP: 10.00%) (P<0.01), indicating that severe restriction had already affected muscle development potential. These results demonstrate that appropriate restriction intensity is necessary to achieve satisfactory compensatory growth effects.

1.3 Timing and Duration of Feed Restriction

The appropriate timing and duration of feed restriction vary depending on animal species, developmental stage, and nutritional status. Camacho et al. [10] applied feed restriction to broiler chickens during different time periods, finding that restriction initiated at 7 days of age yielded the best results, effectively reducing overall mortality, ascites, and leg problems while enabling restricted birds to achieve carcass characteristics comparable to the control group after compensatory growth. Ballay et al. [11] showed that restricting broiler chickens for 6 days before 18 days of age allowed them to achieve compensatory growth by 39 days of age; however, if restriction exceeded 6 days, although feed conversion efficiency improved, body weight remained below the control group. Based on previous studies, feed restriction in broiler chickens is generally applied before 21 days of age for 5–7 days, primarily between 5 and 14 days of age. Studies in other animals indicate that beef cattle are typically restricted between 7 and 10 months of age, while for pigs, restriction should not begin too early due to multiple stress factors during the weaning period. Therefore, developing scientifically based feed restriction programs for different animal species is essential.

1.4 Feed Intake During Compensatory Growth Period

Feed intake is one of the primary factors determining animal growth performance and genetic potential, and it affects body weight gain, feed utilization efficiency, and carcass characteristics. Manal et al. [12] studied feed restriction in pregnant nulliparous rabbit does and found that offspring from all restriction groups exhibited significantly higher feed intake and feed utilization efficiency during later rearing stages compared with the control group (P<0.05). Zubair et al. [13] reported that although restricted broiler chickens had significantly lower basal metabolic rates during the restriction period (P<0.05), increased feed intake during the compensatory growth period was the main factor enabling them to complete compensatory growth. These findings indicate that appropriately increasing dietary provision during the compensatory growth phase can effectively utilize the animal' s compensatory growth capacity.

2. Physiological Effects of Compensatory Growth

2.1 Effects on Protein and Nitrogen Metabolism

Dietary nutritional levels significantly influence protein turnover metabolism, which increases when dietary protein levels are elevated [14]. During the compensatory growth period, increasing dietary nutritional levels results in markedly increased protein deposition. Studies in rats found that when fed low-protein diets, muscle protein turnover rates decreased, but compensatory growth occurred after returning to normal protein diets, accompanied by higher muscle protein synthesis and degradation rates [15]. Turgeon et al. [16] applied early feed restriction followed by compensatory growth in lambs and observed higher protein deposition rates during the early compensatory phase, with no statistical difference in weight gain between restricted and control groups at the end of the compensatory period (P>0.05). Similar results were reported by Lametsch et al. [17] in pigs. These findings suggest that controlling protein intake during early growth and implementing compensatory feeding later can improve feed conversion efficiency and effectively reduce environmental pollution caused by inadequate protein utilization [3].

Compensatory growth is closely related to nitrogen deposition in animals. Lippens et al. [3] restricted Ross broiler chickens from 4 to 7 days of age and found that restricted birds showed higher nitrogen deposition than the control group (P>0.05), with final body weight slightly higher than the control group (P>0.05), achieving hyper-compensatory growth. Ishida et al. [1] obtained similar results in a lysine restriction model in pigs.

2.2 Effects on Immunity

Nutrients are fundamental for promoting immune organ development, and appropriate nutritional levels can enhance animal immunity and reduce disease susceptibility [18]. Liu Xiaogang et al. [19] conducted feed restriction and compensatory growth experiments in Ujimqin lambs, finding that CD4+ T lymphocyte content in blood increased rapidly during the early compensatory growth period (60–90 days of age). At the end of compensatory growth (150 days of age), the CD8+ T lymphocyte content in the protein restriction group was significantly higher than in the control group (P<0.05), while the CD4+/CD8+ T lymphocyte ratio did not differ significantly among groups (P>0.05), indicating that immune function in restricted lambs was enhanced through compensatory growth. Khajavi et al. [20] reported that CD4+ T lymphocyte percentages were significantly higher in restricted broiler chickens after compensatory growth compared with the control group (P<0.05). These results suggest that scientifically implemented feed restriction and compensatory growth can enhance immune function and disease resistance, reducing morbidity and mortality rates.

2.3 Effects on Related Enzyme Activities

Feed restriction can decrease or increase enzyme secretion activities, and these effects may persist after restriction is lifted. Zhan et al. [21] found that after compensatory growth in restricted broiler chickens, activities of malic dehydrogenase (MDH) ($P<0.05$), isocitrate dehydrogenase (ICD) ($P<0.01$), and glucose-6-phosphate dehydrogenase (G-6-PDH) ($P<0.05$) were significantly increased in the liver, with similar results observed in abdominal fat. Chen Junqiang et al. [22] reported that cellulase activity in rumen fluid of Small-tailed Han sheep showed an increasing trend during the compensatory growth period after restriction, with all restriction groups exhibiting higher cellulase activity than the control group at 90 days. He et al. [23] found that both energy and protein restriction in late-gestation ewes affected superoxide dismutase (SOD) activity in the thymus and spleen.

2.4 Effects on Hormones

Hormonal regulation represents a current research hotspot in compensatory growth mechanisms. Yambayamba et al. [24] restricted Hereford crossbred heifers for 95 days and found that growth hormone (GH) concentration in blood was extremely significantly higher in the restricted group than in the control group ($P=0.01$), decreasing to control levels after 31 days of compensatory growth. Insulin-like growth factor I (IGF-I) and insulin (INS) concentrations were also higher in restricted cattle ($P>0.05$). These results indicate that increased early growth rates during compensatory growth are closely associated with the GH-IGF-I-INS axis, consistent with findings by Keogh et al. [25] in bulls. Chaosap et al. [26] confirmed in a pig restriction model that plasma IGF-I concentration in restricted groups increased with elevated dietary nutritional levels during compensatory growth, reaching control group levels after 2 days of compensation ($P>0.05$). Additionally, Zhang Dongmei [27] found that somatostatin receptor concentrations also increased with improved nutritional levels during the compensatory period, suggesting that animals cease unlimited compensatory growth after reaching ecological equilibrium.

2.5 Effects on Related Gene Expression

Animal age, developmental status, hormones, and nutritional levels can all affect gene expression, with nutritional status being particularly crucial. Yang Meixia et al. [28] reported that IGF-I mRNA expression in liver and longissimus dorsi muscle was extremely significantly lower in restricted sheep during the restriction period compared with the control group ($P<0.01$), but increased after compensatory growth with no significant difference from the control group ($P>0.05$), indicating recovery of IGF-I mRNA expression. Similar results were obtained by Zhang Dongmei et al. [29] in lambs. He et al. [23] restricted pregnant ewes and found that after 22 weeks of normal feeding, offspring from restricted dams had significantly higher copper and zinc superoxide dismutase (Cu,Zn-SOD) gene expression in liver and thymus compared with control offspring ($P<0.05$), while peroxiredoxin 2 (PRDX2) gene expression was significantly higher only in the thymus ($P<0.05$). However, Tarry-Adkins et al. [30] found no significant change in pancreatic PRDX2 mRNA expression in 3-month-old offspring from restricted rat dams.

3. Applications of Compensatory Growth in Animal Production

3.1 Application in Poultry Production

High growth rates are characteristic of modern livestock production but can lead to excessive fat deposition and related metabolic diseases. Previous studies have demonstrated that early feed restriction followed by compensatory growth can effectively reduce overall animal mortality [3]. Zhan et al. [21] applied early energy restriction to broiler chickens and found that after compensatory growth, restricted birds showed no statistical differences in body weight, weight gain, dressing percentage, or feed conversion ratio compared with the control group ($P>0.05$), indicating full compensatory growth, though abdominal fat weight was significantly higher in restricted birds ($P<0.05$). Khetani et al. [31] applied quantitative feed restriction to 22-day-old broiler chickens for 2 weeks followed by compensatory growth, finding no significant differences in body weight, overall average daily gain, or overall daily feed intake compared with the control group ($P>0.05$), while average daily gain during the compensatory period was significantly higher ($P<0.05$). Research on compensatory growth in poultry has focused primarily on chickens, with limited reports on other poultry species. Cao Yujuan et al. [32] studied compensatory growth in goslings after restriction and found that the 5% restriction group showed no significant differences in semi-eviscerated weight, eviscerated weight, breast muscle percentage, leg muscle percentage, or abdominal fat percentage compared with the control group ($P>0.05$), while abdominal fat weight was significantly lower ($P<0.05$).

3.2 Application in Swine Production

As living standards improve, consumer demands for meat quality have gradually increased. Madsen et al. [33] applied feed restriction to castrated piglets followed by compensatory growth and found that growth rate and efficiency were significantly higher in restricted groups during the compensatory phase compared with ad libitum-fed groups ($P<0.05$). Appropriate feed restriction and compensatory growth not only fail to impair pig growth performance but can also improve carcass quality. Chaosap et al. [26] found that after restricting 73-day-old piglets, growth rate during the compensatory period was 12.9% higher in restricted groups than in controls ($P<0.05$), with no significant difference in carcass weight between groups after compensatory growth ($P>0.05$). Heyer et al. [34] applied feed restriction to Duroc pigs followed by compensatory growth and reported that average daily gain, average daily feed intake, and gain:feed ratio were all extremely significantly higher in restricted groups during the compensatory period compared with ad libitum-fed groups (P=0.001), with better intramuscular fat deposition in the longissimus dorsi muscle ($P<0.05$), which may explain why restricted pigs reached 110 kg 19 days earlier than ad libitum-fed pigs.

3.3 Application in Herbivore Production

Research on compensatory growth in herbivores has primarily focused on cattle and sheep. Chen Junqiang et al. [22] restricted 3-month-old Small-tailed Han ram lambs for 30 days and found that after compensatory growth, there were no significant differences in apparent nutrient digestibility among groups during the compensatory period ($P>0.05$), though average daily gain increased with restriction intensity, and final body weights did not differ significantly between restricted and ad libitum-fed groups ($P>0.05$). Choi et al. [35] applied feed restriction to Holstein heifers followed by compensatory growth and found that restricted heifers had higher body weight than controls ($P>0.05$), with extremely significantly higher weight gain rates ($P<0.01$) and 9% higher milk production ($P<0.05$). Zhang Chongzhi et al. [9] reported that muscle fiber development was faster in restricted lambs during the compensatory period, with no significant differences in muscle fiber diameter, area, or density among groups ($P>0.05$), indicating compensatory growth effects in restricted lambs.

3.4 Application in Aquaculture

Research on compensatory growth applications in aquatic animals has gradually gained attention. Studies in sticklebacks have shown that compensatory growth can compensate for growth deficits caused by earlier starvation [36]. Wu et al. [37] applied cyclic feeding (1 week starvation and 2 weeks ad libitum feeding) to three-spined sticklebacks and achieved favorable compensatory growth, with weight gain rates in restricted groups exceeding those of controls during the final two phases ($P>0.05$). Additionally, Montserrat et al. [38] starved rainbow trout fry for 1 week followed by compensatory growth and found that growth rate during the compensatory period was significantly higher in the starved group, with final body weight reaching control group levels ($P>0.05$).

Compensatory growth offers high application value in improving animal immunity, increasing market weight, and enhancing nitrogen deposition. However, issues such as optimal restriction intensity and timing, as well as excessive abdominal fat deposition during later stages, require further investigation. Research on potential functions, including promotion of hormone secretion, digestive enzyme activity, and altered gene expression, remains in the exploratory stage. As research on compensatory growth deepens, its expanded application in practice will beneficially promote the healthy development of the animal husbandry industry.

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References

[1] ISHIDA A, KYOYA T, NAKASHIMA K, et al. Nitrogen balance during compensatory growth when changing the levels of dietary lysine from deficiency to sufficiency in growing pigs[J]. Animal Science Journal, 2012, 83(11): 743-749.

[2] MITCHELL A D. Impact of research with cattle, pigs, and sheep on nutritional concepts: body composition and growth[J]. The Journal of Nutrition, 2007, 137(3): 711-714.

[3] LIPPENS M, HUYGHEBAERT G, DE GROOTE G. The efficiency of nitrogen retention during compensatory growth of food-restricted broilers[J]. British Poultry Science, 2002, 43(5): 669-676.

[4] SHARIATMADARI F, TORSHIZI R V. Feed restriction and compensatory growth in chicks: effects of breed, sex, initial body weight and level of feeding[J]. British Poultry Science, 2004, 45(Suppl.1): S52-S53.

[5] WHITAKER K W, TOTOKI K, REYES T M. Metabolic adaptations to early life protein restriction differ by offspring sex and post-weaning diet in the mouse[J]. Nutrition, Metabolism and Cardiovascular Diseases, 2012, 22(12): 1067-1074.

[6] BHASIN K K S, VAN NAS A, MARTIN L J, et al. Maternal low-protein diet or hypercholesterolemia reduces circulating essential amino acids and leads to intrauterine growth restriction[J]. Diabetes, 2009, 58(3): 559-566.

[7] CAO Yujuan. Effects of early energy restriction on compensatory growth in goslings[D]. Master' s thesis. Yangzhou: Yangzhou University, 2014: 11-33.

[8] LIPPENS M, ROOM G, DE GROOTE G, et al. Early and temporary quantitative food restriction of broiler chickens. 1. Effects on performance characteristics, mortality and meat quality[J]. British Poultry Science, 2000, 41(3): 343-354.

[9] ZHANG Chongzhi, GAO Aiwu, HOU Xianzhi, et al. Effects of different nutritional levels on histological properties of lamb muscle[J]. Chinese Journal of Animal Nutrition, 2011, 23(2): 336-342.

[10] CAMACHO M A, SUÁREZ M E, HERRERA J G, et al. Effect of age of feed restriction and microelement supplementation to control ascites on production and carcass characteristics of broilers[J]. Poultry Science, 2004, 83(4): 526-532.

[11] BALLAY M, DUNNINGTON E A, GROSS W B, et al. Restricted feeding and broiler performance: age at initiation and length of restriction[J]. Poultry Science, 1992, 71(3): 440-447.

[12] MANAL A F, TONY M A, EZZO O H, et al. Feed restriction of pregnant nulliparous rabbit does: consequences on reproductive performance and maternal behaviour[J]. Animal Reproduction Science, 2010, 120(1/2/3/4): 179-186.

[13] ZUBAIR A K, LEESON S. Effect of early feed restriction and realimentation on heat production and changes sizes of digestive organs of male broilers[J]. Poultry Science, 1994, 73(4): 529-538.

[14] KOBAYASHI H, BØRSHEIM E, ANTHONY T G, et al. Reduced amino acid availability inhibits muscle protein synthesis and decreases activity of initiation factor eIF2B[J]. American Journal of Physiology: Endocrinology and Metabolism, 2003, 284(3): E488-E498.

[15] JONES S J, STARKEY D L, CALKINS C R, et al. Myofibrillar protein turnover in feed-restricted and realimented beef cattle[J]. Journal of Animal Science, 1990, 68(9): 2707-2715.

[16] TURGEON O A, Jr, BRINK D R, BARTLE S J, et al. Effects of growth rate and compensatory growth on body composition in lambs[J]. Journal of Animal Science, 1986, 63(3): 770-780.

[17] LAMETSCH R, KRISTENSEN L, LARSEN M R, et al. Changes in the muscle proteome after compensatory growth in pigs[J]. Journal of Animal Science, 2006, 84(4): 918-924.

[18] LIU Haigang, HAN Jie, HONG Yu, et al. Research progress on effects of dietary nutrients on animal immune function[J]. Feed Industry, 2009, 30(15): 14-16.

[19] LIU Xiaogang. Effects of nutritional restriction and compensation on visceral organs and CD4+ and CD8+ T lymphocytes in blood of lambs[D]. Hohhot: Inner Mongolia Agricultural University, 2010.

[20] KHAJAVI M, RAHIMI S, HASSAN Z M, et al. Effect of feed restriction early in life on humoral and cellular immunity of two commercial broiler strains under heat stress conditions[J]. British Poultry Science, 2003, 44(3): 490-497.

[21] ZHAN X A, WANG M, REN H, et al. Effect of early feed restriction on metabolic programming compensatory growth broiler chickens[J]. Poultry Science, 2007, 86(4): 654-660.

[22] CHEN Junqiang, DING Luming, GAO Qiang, et al. Effects of feed restriction and nutritional compensation on growth performance, digestion and metabolism, and rumen fluid cellulase activity in Small-tailed Han sheep[J]. Chinese Journal of Animal Nutrition, 2015, 27(7): 2085-2093.

[23] HE Z X, SUN Z H, TAN Z L, et al. Effects of maternal protein or energy restriction during late gestation on antioxidant status of plasma and immune tissues in postnatal goats[J]. Journal of Animal Science, 2012, 90(12): 4319-4326.

[24] YAMBAYAMBA E S, PRICE M A, FOXCROFT G R. Hormonal status, metabolic changes, and resting metabolic rate in beef heifers undergoing compensatory growth[J]. Journal of Animal Science, 1996, 74(1): 57-69.

[25] KEOGH K, WATERS S M, KELLY A K, et al. Effect of feed restriction and subsequent re-alimentation on hormones and genes of the somatotropic axis in cattle[J]. Physiological Genomics, 2015, 47(7): 264-273.

[26] CHAOSAP C, PARR T, WISEMAN J. Effect of compensatory growth on performance, carcass composition and plasma IGF-1 in grower finisher pigs[J]. Animal, 2011, 5(5): 749-756.

[27] ZHANG Dongmei. Effects of nutritional restriction and compensation on growth-related indices in pituitary, liver, and duodenum and blood hormone levels in Mongolian lambs[D]. Master' s thesis. Hohhot: Inner Mongolia Agricultural University, 2014: 11-33.

[28] YANG Meixia, WU Cuilan, QI Jingwei, et al. Effects of nutritional restriction and compensatory growth on insulin-like growth factor-1 (IGF-1) mRNA expression levels in Mongolian sheep[J]. Journal of Inner Mongolia Agricultural University, 2007, 28(2): 9-12.

[29] ZHANG Dongmei, HOU Xianzhi, YANG Jinli, et al. Effects of dietary energy and protein restriction and compensation on liver weight, hepatocyte proliferation and hypertrophy, and gene expression of growth hormone receptor and insulin-like growth factor in Mongolian lambs[J]. Chinese Journal of Animal Nutrition, 2013, 25(7): 1632-1640.

[30] TARRY-ADKINS J L, CHEN J H, SMITH N S, et al. Poor maternal nutrition followed by accelerated postnatal growth leads to telomere shortening and increased markers of cell senescence in rat islets[J]. FASEB Journal, 2009, 23(5): 1521-1528.

[31] KHETANI T L, NKUKWANA T T, CHIMONYO M, et al. Effect of quantitative feed restriction on broiler performance[J]. Tropical Animal Health and Production, 2009, 41(3): 379-384.

[32] CAO Yujuan, WANG Zhiyue, SUN Hongnuan, et al. Effects of early energy restriction on growth performance and visceral organ development in goslings[J]. Chinese Journal of Animal Nutrition, 2014, 26(1): 90-97.

[33] MADSEN J G, BEE G. Compensatory growth feeding strategy does not overcome negative effects on growth and carcass composition of low birth weight pigs[J]. Animal, 2015, 9(3): 427-436.

[34] HEYER A, LEBRET B. Compensatory growth response in pigs: effects on growth performance, composition of weight gain at carcass and muscle levels, and meat quality[J]. Journal of Animal Science, 2007, 85(3): 769–778.

[35] CHOI Y J, HAN I K, WOO J H, et al. Compensatory growth in dairy heifers: the effect of a compensatory growth pattern on growth rate and lactation performance[J]. Journal of Dairy Science, 1997, 80(3): 519–524.

[36] INNESS C L W, METCALFE N B. The impact of dietary restriction, intermittent feeding and compensatory growth on reproductive investment and lifespan in a short-lived fish[J]. Proceedings of the Royal Society of London Series B: Biological Sciences, 2008, 275(1644): 1703–1708.

[37] WU L, XIE S, CUI Y, et al. Effect of cycles of feed deprivation on growth and food consumption of immature three-spined sticklebacks and European minnows[J]. Journal of Fish Biology, 2003, 62(1): 184–194.

[38] MONTSERRAT N, GABILLARD J C, CAPILLA E, et al. Role of insulin, insulin-like growth factors, and muscle regulatory factors in the compensatory growth of the trout (Oncorhynchus mykiss)[J]. General and Comparative Endocrinology, 2007, 150(3): 462–472.

Note: Figure translations are in progress. See original paper for figures.