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Effects of Maternal and Progeny Dietary Vitamin Regimens on the Performance of Ducklings

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This study evaluated the interaction effect of maternal and progeny vitamin regimens on the performance of ducklings. At 38 weeks of age, 780 female and 156 male duck breeders were fed either regular or high vitamin premix diet (maternal high premix had higher levels of all vitamins except K_3 than maternal regular premix) for 16 weeks. Ducklings hatched from eggs laid at the end of the duck breeder trial were kept separate according to maternal treatment and were fed 2 levels of vitamin premix (NRC and high, progeny high premix had higher levels of all vitamins except biotin than progeny NRC premix) for 35 days. Body weight ($P<0.001$) and tibia ash ($P=0.033$) of 1-day-old ducklings and serum total superoxide dismutase activity of 14-day-old ducklings ($P=0.027$) were increased by maternal high vitamin premix. Progeny high vitamin premix increased body weight (14 days, $P=0.019$; 35 days, $P=0.034$), body weight gain (1–14 days, $P=0.021$; 1–35 days, $P=0.034$), gain:feed ratio (1–14 days, $P<0.001$), feed intake (15–35 days, $P=0.037$), serum total antioxidant capacity (14 days, $P=0.048$; 35 days, $P=0.047$), and serum calcium (14 days, $P=0.007$), and decreased serum malondialdehyde (14 days, $P=0.038$; 35 days, $P=0.031$) of ducklings. Maternal vitamin premix–progeny vitamin premix interaction significantly affected body weight (14 days, $P=0.029$), body weight gain (1–14 days, $P=0.029$), and feed intake (1–14 days, $P=0.018$) of progeny ducklings. Briefly, progeny NRC premix decreased the growth performance (days 1–14) of ducklings from maternal regular vitamin group, but not duckling from maternal high vitamin group. The results demonstrate a shortcoming of current vitamin recommendations for ducklings and suggest that the vitamin needs of starter ducklings can be met by either maternal or progeny vitamin supplementation.

Key words: duck, interaction, maternal, progeny, vitamin

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Introduction

The scientific literature indicates that maternal nutrition is an important factor influencing embryonic development and may have lifelong consequences for progeny health (Godfrey *et al*., 1996; Molina *et al*., 2008; Liu *et al*., 2011). Among all animal species, birds are unique in that embryonic development takes place outside the body of the mother hen, thus requiring maternal transfer of nutrients to the egg (Moran, 2007). Interestingly, the nutritional composition of breeder eggs, which may affect fetal preprogramming and further change the structure, physiology, and metabolism of the progeny, can be changed through the maternal diet (Naber, 1979). For example, in a study by Leeson and Caston (2003), the egg contents of all vitamins (except vitamin K) were increased when layers were fed a diet with 3–10 times more supplemental vitamins. Notably, vitamin enrichment of eggs not only can be used to produce functional products (Stadelman, 1999), but also benefits the antioxidant system and bone metabolism of the developing embryo (Surai, 2000; Atencio *et al*., 2006), thereby influencing the growth, development, and health status of the offspring (Atencio *et al*., 2005b; Lin *et al*., 2005).

In the early days post hatching, the nutritional status of young birds is interactively affected by both maternal and dietary nutrients (Cherian and Sim, 2003). As birds age, the maternal effect begins to wane and diet becomes the dominant factor in growth performance (Koutsos *et al*., 2007). Surai (2000) reported that the inclusion of 40 to 200 mg/kg vitamin E in a commercial diet increased the vitamin E concentration in the egg sac membrane of 1-day-old chicks, in the brain of 1- and 5-day-old chicks, and in the liver of 1-,

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5-, and 10-day-old chicks. Driver *et al*. (2006) pointed out that maternal vitamin D_3 status directly affects the bone metabolism and growth performance of 16-day-old progeny chicks. Other researchers have also reported on the influence of maternal vitamin nutrition on the vitamin status of offspring (Semba *et al*., 1994; Liu *et al*., 2011). Therefore, maternal vitamin status should be seriously considered when evaluating the vitamin requirement of poultry progeny. However, although the effect of maternal vitamin on progeny health in poultry has been extensively reported on (Surai, 2000; Lin *et al*., 2005; Atencio *et al*., 2006; Peng *et al*., 2013), the interaction between maternal and progeny vitamin has been rarely investigated.

In this study, we evaluated the effects of maternal dietary vitamin premixes on growth performance, antioxidant status, and tibia quality of progeny ducklings under different vitamin regimes.

Materials and Methods

All procedures were approved by the Animal Care and Use Committee of Sichuan Agricultural University.

Duck Breeder Experiment

Seven hundred and eighty Cherry Valley duck breeder females and 156 males of 38 weeks old were completely randomized over 6 floor pens (130 females and 26 males per pen). The 6 pens were divided into 2 experimental groups that were fed either regular vitamin premix diet or high-vitamin premix diet for 16 weeks (Table 1). The maternal regular vitamin premix was formulated to simulate commercial premixes used in the duck breeder industry in China. The maternal high-vitamin premix was designed according to the recommendations in the DSM Vitamin Supplementation Guidelines (DSM Nutritional Products, 2011) and had higher levels of all vitamins except K_3 than the regular vitamin

Table 1. **Composition and nutrient levels of the basal diet**

Item (% unless noted)	Duck breeder	Progeny duckling	
		1–14 days	15–35 days
Corn	24.40	51.00	46.50
Wheat bran	—	8.00	15.00
Wheat flour	20.00	—	—
Rice bran	15.00	5.00	8.00
Soybean meal, 43%	22.00	20.00	8.00
Rice bran meal	2.90	—	—
Rapeseed meal	5.00	5.00	8.00
Cottonseed meal	—	5.00	6.00
Meat and bone meal	3.50	—	—
Rapeseed oil	—	1.21	3.88
Calcium carbonate	6.30	0.985	0.960
Dicalcium phosphate, $2H_2O$	—	1.490	1.175
L-Lysine-H_2SO_4	0.13	—	—
L-Lysine-HCl	—	0.24	0.27
D,L-Methionine	0.12	0.211	0.126
Threonine, 98.5%	—	0.045	0.044
Tryptophan, 98.5%	—	0.077	0.032
Sodium chloride	0.30	0.40	0.40
Choline chloride, 50%	0.10	0.15	0.10
Bentonite	—	0.592	0.913
Mineral premix[1]	0.15	0.50	0.50
Vitamin premix[2]	0.10	0.10	0.10
Nutrient content			
ME (Kcal/kg, calculated)	2762	2750	2814
CP (analyzed)	20.68	19.83	17.69
Calcium (analyzed)	3.02	0.95	0.85
Total phosphorus (analyzed)	0.81	0.74	0.78
Nonphytate phosphorus (calculated)	0.303	0.418	0.378
Lysine (calculated)	1.087	1.083	0.893
Methionine (calculated)	0.446	0.486	0.365
Threonine (calculated)	0.749	0.726	0.606

[1] Supplied per kilogram of maternal diet: copper, 12 mg; iron, 70 mg; zinc, 80 mg; manganese, 100 mg; selenium, 0.25 mg; iodine, 0.2 mg. Supplied per kilogram of progeny diet: copper, 8 mg; iron, 80 mg; zinc, 90 mg; manganese, 70 mg; selenium, 0.3 mg; iodine, 0.4 mg.

[2] Composition of the vitamin premixes for duck breeders and progeny ducklings is listed in Table 2.

Table 2. **Composition of the vitamin premixes for duck breeders and progeny ducklings**

Item[1,2]	Duck breeder[3]		Progeny duckling[4]	
	Regular	High	NRC	High
Vitamin A (IU)	10000	15000	2500	15000
Vitamin D_3 (IU)	3000	4000	400	5000
Vitamin K_3 (mg)	5.0	5.0	0.5	5.0
Vitamin E (IU)	30	100	10	80
Vitamin B_1 (mg)	4.0	5.0	1.8	3.0
Vitamin B_2 (mg)	6	16	4	9
Vitamin B_6 (mg)	4.0	5.0	2.5	7.0
Vitamin B_{12} (mg)	0.015	0.025	0.010	0.040
Nicotinic acid (mg)	50	60	55	80
Pantothenic acid (mg)	15	20	11	15
Biotin (mg)	0	0.2	0.15	0.15
Folic acid (mg)	1.00	2.50	0.55	2.00
Vitamin C (mg)	—	—	—	200
25-hydroxycholecalciferol (mg)	—	—	—	0.069

[1] Supplied per kilogram of diet.
[2] All vitamin premixes used in this trial were provided by DSM Ltd. (Chengdu, Sichuan, China).
[3] The maternal regular vitamin premix was formulated to simulate commercial premixes used in the duck breeder industry in China and the maternal high-vitamin premix was developed according to the recommendations in DSM Vitamin Supplementation Guidelines (DSM Nutritional Products Ltd., 2011).
[4] The progeny NRC vitamin premix was formulated based on NRC (1994) recommendations, and the progeny high-vitamin premix was developed based on the levels in DSM Vitamin Supplementation Guidelines (DSM Nutritional Products Ltd., 2011).

premix (Table 2). Feed and water were supplied *ad libitum*, and a 17:7 h light/dark photoperiod was applied during the duck breeder trial.

Eggs from each pen were collected and weighed every morning. Total eggs, total egg mass, and total settable eggs produced by per hen during the 16-week trial were calculated. On the last 2 days of the maternal study, 126 settable eggs per pen were randomly chosen and incubated in a Yiai 12096 incubator (Qingdao, Shandong, China). Briefly, the settable eggs were stored for 3 days at 15–16℃ under 70–75% relative humidity (RH) before being transferred to the incubator. The eggs were washed with a benzalkonium bromide-based sanitizer (0.1%, 40℃) and allowed to dry. The incubation temperature was controlled at 37.8, 37.6, and 37.5 ℃ during days 1–14, 15–21, and 22–25, respectively, and RH at 60%. Eggs were candled on day 7 of incubation and clear eggs were opened to determine macroscopic infertility or embryonic mortality. On day 26 of incubation, living embryos were transferred to a hatcher at 36.5℃ and with 70% RH. Two days later, ducklings were taken out of the hatcher, weighed, and classified. Ducklings were considered healthy when they were clean and dry, were free of abnormalities, had complete umbilical scarring, and had bright eyes. Fertility, hatchability of fertile eggs, hatchability of settable eggs, and percentage of healthy ducklings were calculated.

Progeny Experiment

Ducklings hatched in the duck breeder experiment were kept separate according to the maternal diet. Twelve newly hatched healthy ducklings from each maternal treatment were selected and euthanized for liver and tibia samples (stored at −20℃) for the analysis of liver antioxidant status and tibia quality. At the same time, 240 healthy ducklings from each maternal treatment were randomly selected and divided over 16 pens, with 15 ducklings per pen. The pens were randomly assigned to 2 diets consisting of "NRC vitamin premix" formulated based on National Research Council recommendations (NRC, 1994) or high-vitamin premix (Table 1) developed based on the levels mentioned in the DSM Vitamin Supplementation Guidelines (DSM Nutritional Products, 2011). The progeny high-vitamin premix had higher levels of all vitamins except biotin than the NRC vitamin premix (Table 2). Feed and water were provided for *ad libitum* throughout the 35-day feeding trial (starter phase: days 1–14; grower phase: days 15–35). Body weight (BW) and feed intake (FI) of ducklings were recorded at 14 and 35 days of age. Average FI and BW gain (BWG) were corrected for mortality when calculating the gain: feed (G:F) ratio for each cage. On days 14 and 35 of the progeny trial, 1 bird from each pen was randomly selected and bled (blood was centrifuged at 1,200×*g* for 10 min at 4℃ to obtain serum, which was stored at −20℃) for calcium, phosphorus, and antioxidant status determination, and then euthanized for tibia samples (stored at −20℃) for the analysis of tibia quality.

Sample Analyses

Malonaldehyde (MDA, a marker of lipid peroxidation; day 1, liver; days 14 and 35, serum) was measured using a commercial kit (Nanjing Jiancheng Bioengineering Institute, Nanjing, Jiangsu, China) based on the thiobarbituric acidreactive substances method (Jentzsch *et al*., 1996). The absorbance of the colored product was measured at 532 nm using a Multiskan Spectrum reader (Model 1500; Thermo Scientific, Nyon, Switzerland). The activity of total superoxide dismutase (T-SOD; day 1, liver; days 14 and 35, serum) was determined by the hydroxylamine method (Oyanagui, 1984) using the Nanjing Jiancheng Bioengineering Institute T-SOD kit. Absorbance of the colored product was measured at 550 nm. One unit of T-SOD was defined as the amount of enzyme that inhibited the reaction by 50%. The ferric reducing/antioxidant power method (Benzie and Strain, 1999) was used to detect the level of total antioxidant capacity (T-AOC; day 1, liver; days 14 and 35, serum) using the Nanjing Jiancheng Bioengineering Institute T-AOC kit. Absorbance of the colored product was measured at 520 nm. One T-AOC unit was defined as the amount of antioxidants that caused a 0.01 increase in absorbance per minute. Protein carbonyl (a major product of protein oxidation; day 1, liver; days 14 and 35, serum) was analyzed by the 2,4-dinitrophenylhydrazine method (Reznick *et al*., 1992) using the Nanjing Jiancheng Bioengineering Institute protein carbonyl assay kit; the absorbance at 370 nm was measured. For the determination of serum (days 14 and 35) calcium and phosphorus levels using commercial kits from Nanjing Jiancheng Bioengineering Institute, the absorbance at 610 and 660 nm, respectively, was measured. Adherent tissues were removed before the determination of tibia (days 1, 14, and 35) strength and ash content. Tibia-breaking strength was recorded using a TA-XTPlus Texture Analyser (Lotun Science, Beijing, China) at room temperature. The bone fragments were oven-dried at 108℃ for 24 h and extracted by refluxing ethyl ether in a Soxhlet apparatus for 16 h. Extracted tibias were oven-dried at 108℃ for 24 h and ashed in a muffle furnace for 24 h at 600℃ (method 942.05; AOAC, 2006).

Statistical Analysis

Productive and reproductive performance (Table 3) of duck breeders were analyzed by the Student's *t*-test for independent samples using SPSS 17.0 (SPSS Inc., Chicago, IL). Performance data of progeny ducklings (Tables 4, 5, and 6) were analyzed by ANOVA as a 2×2 factorial (maternal vitamin premix × progeny vitamin premix) using GLM procedures in SPSS 17.0. Main effects and interactions were determined. Duncan's test was applied when any of the interactions showed significance. Pen was the experimental unit. Data are shown as the LS mean and pooled SEM. Results were considered significantly different at $P < 0.05$, and trends at $0.05 \leq P < 0.1$.

Results

Productive and Reproductive Performance of Duck Breeders

The results of laying performance, fertility, hatchability, and duckling quality are shown in Table 3. High-vitamin premix duck breeder diet did not affect ($P > 0.05$) laying performance, fertility, and hatchability when compared with the regular vitamin premix diet. Interestingly, newly hatched ducklings from the maternal high-vitamin premix group had higher BW ($P < 0.001$) and tibia ash content ($P = 0.033$), and tended to have higher liver T-SOD activity ($P = 0.099$) than ducklings from the maternal regular vitamin premix group. Antioxidant status and tibia strength of 1-day-old progeny ducklings were not influenced by maternal vitamin regimens ($P > 0.05$).

Performance of Progeny Ducklings

Growth performance of progeny ducklings was not influenced ($P > 0.05$, Table 4) by maternal vitamin regimens. However, dietary high-vitamin premix significantly increased the BW of 14-day-old ($P = 0.019$) and 35-day-old ($P = 0.034$) ducklings. Additionally, dietary high-vitamin premix increased BWG (1–14 days, $P = 0.021$; 1–35 days, $P = 0.034$), G:F ratio (1 to 14 d, $P < 0.001$), and FI (15–35 days, $P = 0.037$), and tended to increase BWG (15–35 days, $P = 0.062$) and FI (1–35 days, $P = 0.071$) of ducklings. Interestingly, maternal vitamin premix–progeny vitamin premix interaction significantly affected BW at 14 days ($P = 0.029$), BWG at days 1–14 ($P = 0.029$), and FI at days 1–14 ($P = 0.018$) in progeny ducklings. Briefly, dietary NRC vitamin premix lowered BW at 14 days and BWG over days 1–14 in ducklings from the maternal regular vitamin premix group, but not in those from the maternal high-vitamin premix group. Decreased FI on days 1–14 was observed in ducklings from the maternal high-vitamin premix group fed the high-vitamin premix diet.

The antioxidant statuses of progeny ducklings are shown in Table 5. Maternal high-vitamin premix increased serum T-SOD activity ($P = 0.027$) of 14-day-old ducklings. Dietary high-vitamin premix increased serum T-AOC of 14- ($P = 0.048$) and 35-day-old ($P = 0.047$) ducklings, and decreased serum MDA of 14- ($P = 0.038$) and 35-day-old ($P = 0.031$) ducklings. No maternal vitamin premix–progeny vitamin premix interaction ($P > 0.05$) was observed in the antioxidant status of progeny ducklings.

Serum calcium, serum phosphorus, and tibia quality of progeny ducklings were not affected by maternal vitamin regimens ($P > 0.05$, Table 6). However, dietary high-vitamin premix increased serum calcium ($P = 0.007$) of 14-day-old ducklings. Interestingly, a maternal vitamin premix–progeny vitamin premix interaction effect ($P = 0.039$) on serum calcium was noted for 35-day-old ducklings. Dietary high-vitamin premix increased 35-day serum calcium in ducklings from the maternal high-vitamin premix group, but not in ducklings from the maternal regular vitamin premix group.

Discussion

Egg production and hatchability have long been used as key metrics to evaluate the vitamin requirements of poultry breeders (NRC, 1994). However, with the growing evidence of the potential of vitamins to be used as so-called "nutraceuticals" to improve poultry health and wellbeing, more parameters, such as antioxidant status, bone quality, immune response, and behavior, have been used to assess vitamin needs (Habibian *et al*., 2014; Lu *et al*., 2014; Saunders-Blades and Korver, 2015). Most vitamins, especially fat-

Table 3. **Effects of dietary vitamin regimens on the productive and reproductive performance of duck breeders**

Item	Vitamin premix[1]		SEM[2]	*P*-value
	Regular	High		
Laying performance				
Total produced eggs/hen housed (n)	88.88	87.70	1.42	0.725
Total egg mass/hen housed (kg)	7.99	7.84	0.15	0.682
Total settable eggs/hen housed (n)	86.59	85.63	1.45	0.778
Fertility and hatchability				
Fertility (%)	89.15	89.63	1.04	0.847
Hatchability of fertile eggs (%)	92.92	93.20	1.05	0.910
Hatchability of settable eggs (%)	82.80	83.52	0.96	0.753
Percentage of healthy ducklings (%)	92.33	92.47	1.29	0.963
Duckling quality[3]				
BW (g)	52.6[b]	53.7[a]	0.13	<0.001
Liver antioxidant status				
MDA (nmol/mg protein)	5.41	4.23	0.38	0.121
T-SOD (U/mg protein)	189.65	225.43	10.67	0.099
T-AOC (U/mg protein)	4.10	5.22	0.48	0.246
Protein carbonyl (nmol/mg protein)	31.68	35.00	1.34	0.224
Tibia quality				
Strength (kg of force)	1.25	1.27	0.04	0.907
Ash (%)	36.72[b]	37.69[a]	0.23	0.033

[a, b] Different superscripts in a row indicate significant differences ($P \leq 0.05$).
[1] The maternal regular vitamin premix was formulated to simulate commercial premixes used in the duck breeder industry in China and the maternal high-vitamin premix was developed according to the recommendations in DSM Vitamin Supplementation Guidelines (DSM Nutritional Products Ltd., 2011).
[2] SEM, standard error of the mean
[3] BW=body weight, MDA=malondialdehyde, T-SOD=total superoxide dismutase, T-AOC=total antioxidant capacity

soluble vitamins, are deposited in the eggs in proportion to diet inclusion (Leeson and Caston, 2003), and subsequently affect the embryonic development and post-hatch life of progeny chicks (Surai, 2000; Lin *et al*., 2005; Driver *et al*., 2006). Development of high-quality progeny chicks therefore dictates elevated maternal dietary vitamins. Unfortunately, little attention has been paid to re-evaluating vitamin requirements of poultry, especially duck, breeders.

In the current study, an increase in dietary vitamin contents from the levels commonly used in the Chinese duck breeder industry to those recommended by DSM Nutritional Products Ltd. (2011) did not affect laying performance, fertility, and hatchability in duck breeders; however, interestingly, it increased BW and tibia ash of newly-hatched ducklings. The relationship between maternal vitamin status and 1-day-old progeny BW has been rarely investigated; however, greater BWG of progeny during the first few days post hatching was achieved by maternal high vitamin (e.g., vitamins A and D) supplementation (Shah and Rajalakshmi, 1984; Atencio *et al*., 2005a). Atencio *et al*. (2006) reported that the maternal vitamin D_3 level for maximum body ash of progeny broilers at day 1 was >2,000 IU/kg. Increased tibia ash content of 1-day-old chicks was observed when maternal vitamin D_3 was increased from 0 to 4,000 IU/kg (Atencio *et al*., 2005b). Accordingly, the increased vitamin D_3 level in our maternal high-vitamin premix (4,000 IU/kg vitamin D_3) may have contributed to the improved tibia quality in 1-day-old progeny ducklings. While the maternal regular vitamin premix met the requirements of duck breeders for egg production and hatchability, more maternal vitamin might be needed for better duckling quality.

The literature on vitamin supplementation in ducklings is surprisingly scarce. Although the NRC has published vitamin requirements for White Pekin ducks (NRC, 1994), the references in the report are meager and all values were estimated based on data obtained from animals of other ages or species. Therefore, the NRC estimates are often criticized as not representative of the levels currently used in the duck industry. In this study, increased growth performance was observed in ducklings fed a diet with high-vitamin premix designed according to the recommendations in the DSM Vitamin Supplementation Guidelines. These observations clearly demonstrate a shortcoming in the current NRC (1994) vitamin recommendations for ducks and are highly consistent with the view of Leeson (2007) that the vitamin requirements of poultry require re-evaluation. Interestingly, maternal and progeny dietary vitamin regimens interactively affected growth performance in the first 14 days post hatching. When using growth performance as the criterion, ducklings from the maternal high-vitamin group had lower vitamin require-

Table 4. **Effects of maternal and progeny dietary vitamin regimens on the growth performance of ducklings**

Item[1]	Maternal regular[2]		Maternal high		SEM[4]	Main effect means				*P*-value		
						Maternal		Progeny				
	Progeny NRC[3]	Progeny High	Progeny NRC	Progeny High		Regular	High	NRC	High	Maternal vitamin	Progeny vitamin	Interac-tion
1 to 14 d												
14 d BW (g)	651^{b}	689^{a}	676^{a}	677^{a}	4.43	670	677	664^{b}	683^{a}	0.393	0.019	0.029
BWG (g)	599^{b}	636^{a}	622^{a}	624^{a}	4.44	617	623	611^{b}	630^{a}	0.482	0.021	0.029
G:F ratio (kg:kg)	0.62	0.64	0.62	0.65	0.01	0.63	0.64	0.62^{b}	0.65^{a}	0.162	<0.001	0.397
FI (g)	966^{ab}	986^{ab}	996^{a}	952^{b}	6.82	976	974	981	969	0.877	0.371	0.018
15 to 35 d												
35 d BW (g)	2567	2664	2623	2691	19.48	2616	2657	2595^{b}	2678^{a}	0.276	0.034	0.699
BWG (g)	1916	1976	1947	2014	16.75	1946	1980	1931	1995	0.299	0.062	0.916
G:F ratio (kg:kg)	0.45	0.43	0.44	0.46	0.01	0.44	0.45	0.45	0.44	0.439	0.666	0.380
FI (g)	4259	4537	4394	4430	38.32	4398	4412	4327^{b}	4483^{a}	0.851	0.037	0.101
1 to 35 d												
BWG (g)	2515	2612	2569	2637	19.48	2563	2603	2542^{b}	2624^{a}	0.290	0.034	0.698
G:F ratio (kg:kg)	0.48	0.48	0.48	0.49	0.01	0.48	0.49	0.48	0.48	0.214	0.628	0.107
FI (g)	5205	5498	5360	5359	41.39	5351	5359	5282	5428	0.917	0.071	0.069

[a, b] Different superscripts in a row indicate significant differences ($P \leq 0.05$).
[1] BW=body weight, BWG=body weight gain, G:F ratio=gain:feed ratio, FI=feed intake
[2] The maternal regular vitamin premix was formulated to simulate commercial premixes used in the duck breeder industry in China and the maternal high-vitamin premix was developed according to the recommendations in DSM Vitamin Supplementation Guidelines (DSM Nutritional Products Ltd., 2011).
[3] The progeny NRC vitamin premix was formulated based on NRC (1994) recommendations and the progeny High vitamin premix was developed based on the levels in DSM Vitamin Supplementation Guidelines (DSM Nutritional Products Ltd., 2011).
[4] SEM, standard error of the mean

Table 5. **Effects of maternal and progeny dietary vitamin regimens on the serum antioxidant status of ducklings**

Item[1]	Maternal Regular[2]		Maternal High		SEM[4]	Main effect means				*P*-value		
						Maternal		Progeny				
	Progeny NRC[3]	Progeny High	Progeny NRC	Progeny High		Regular	High	NRC	High	Maternal vitamin	Progeny vitamin	Interac-tion
MDA (nmol/L)												
14 d	9.22	7.57	8.32	7.57	0.29	8.40	7.95	8.77^{a}	7.57^{b}	0.418	0.038	0.416
35 d	9.12	8.64	9.54	8.63	0.16	8.88	9.08	9.33^{a}	8.64^{b}	0.514	0.031	0.490
T-SOD (U/L)												
14 d	60.40	59.52	65.87	65.80	1.31	59.96^{b}	65.84^{a}	63.13	62.66	0.027	0.851	0.873
35 d	57.20	67.34	65.40	68.28	2.32	62.27	66.84	61.30	67.81	0.327	0.167	0.435
AOC (U/L)												
14 d	6.49	7.80	6.59	7.46	0.27	7.15	7.02	6.54^{b}	7.63^{a}	0.819	0.048	0.684
35 d	6.77	7.88	6.80	7.88	0.27	7.32	7.34	6.78^{b}	7.88^{a}	0.980	0.047	0.975
Protein carbonyl (nmol/mg protein)												
14 d	1.69	1.33	1.44	1.20	0.14	1.51	1.32	1.57	1.27	0.511	0.304	0.843
35 d	2.70	2.65	2.42	2.01	0.21	2.68	2.22	2.56	2.33	0.296	0.600	0.668

[1] MDA=malondialdehyde, T-SOD=total superoxide dismutase, T-AOC=total antioxidant capacity
[2] The maternal regular vitamin premix was formulated to simulate commercial premixes used in the duck breeder industry in China and the maternal high-vitamin premix was developed according to the recommendations in DSM Vitamin Supplementation Guidelines (DSM Nutritional Products Ltd., 2011).
[3] The progeny NRC vitamin premix was formulated based on NRC (1994) recommendations and the progeny high-vitamin premix was designed based on the levels in DSM Vitamin Supplementation Guidelines (DSM Nutritional Products Ltd., 2011).
[4] SEM, standard error of the mean

Table 6. **Effects of maternal and progeny dietary vitamin regimens on serum calcium, serum phosphorus, and tibia quality of ducklings**

Item	Maternal Regular[1]		Maternal High		SEM[3]	*P*-value		
	Progeny NRC[2]	Progeny High	Progeny NRC	Progeny High		Maternal vitamin	Progeny vitamin	Interaction
Serum calcium (mmol/L)								
14 d	1.73	2.07	1.87	2.10	0.05	0.374	0.007	0.597
35 d	1.47[ab]	1.37[b]	1.30[b]	1.81[a]	0.08	0.374	0.155	0.039
Serum phosphorus (mmol/L)								
14 d	4.81	4.80	4.66	4.96	0.07	0.986	0.298	0.278
35 d	4.45	4.37	4.63	4.56	0.13	0.509	0.801	0.979
Tibia strength (kg of force)								
14 d	7.96	8.88	8.13	8.33	0.21	0.670	0.207	0.413
35 d	19.36	20.24	20.04	19.69	0.39	0.933	0.744	0.448
Tibia ash (%)								
14 d	50.33	50.75	49.72	50.22	0.51	0.592	0.665	0.971
35 d	55.85	55.41	57.02	57.64	0.73	0.265	0.949	0.727

[a, b] Different superscripts in a row indicate significant differences ($P \leq 0.05$).

[1] The maternal regular vitamin premix was formulated to simulate commercial premixes used in the duck breeder industry in China and the maternal high-vitamin premix was developed according to the recommendations in DSM Vitamin Supplementation Guidelines (DSM Nutritional Products Ltd., 2011).

[2] The progeny NRC vitamin premix was formulated based on NRC (1994) recommendations and the progeny high-vitamin premix was designed based on the levels in DSM Vitamin Supplementation Guidelines (DSM Nutritional Products Ltd., 2011).

[3] SEM, standard error of the mean

ments (1–14 days) than those from the maternal regular vitamin group. These results are consistent with previous reports with regard to vitamins A, D_3, E, and pantothenic acid (Hill *et al*., 1961; Beer *et al*., 1963; Ameenuddin *et al*., 1986; Atencio *et al*., 2005a) and corroborate the importance of maternal-to-progeny vitamin flow. In this study, the increased BW and tibia quality in 1-day-old ducklings may have further benefited growth in the starter days. In addition, increased vitamin deposition in the yolk sac and other tissues has been indicated to be of great importance for the growth and health of newly hatched chicks (Shah and Rajalakshmi, 1984; Surai, 2000; Atencio *et al*., 2005a). In this regard, the current results suggest that the vitamin needs of ducklings can likely be met either by maternal or progeny supplementation.

The use of dietary antioxidants to relieve oxidative stress, one of the major factors negatively influencing the growth and wellbeing of birds in intensively reared poultry, is well documented. A multitude of studies have demonstrated the antioxidant properties of vitamins, such as vitamins A, C, and E (Sies and Stahl, 1995; Surai *et al*., 2000). In this study, dietary high-vitamin premix increased total antioxidant capacity and decreased lipid peroxidation in 14- and 35-day-old ducklings. Of particular interest is the increased SOD level observed in ducklings from the maternal high-vitamin premix group. The effects of dietary vitamins on antioxidant enzyme activities remain controversial (Musalmah *et al*., 2002; Beytut and Aksakal, 2003). Generally, dietary antioxidants are thought to act in a non-enzymatic way (Brennan *et al*., 2000). However, Lin *et al*. (2005) reported that pullets fed a high-vitamin E (160 mg/kg) diet had progeny chicks with greater brain SOD than those fed 0 or 40 mg/kg vitamin E. Similarly, plasma SOD activity was increased in chicks obtained from canthaxanthin-enriched eggs (Zhang *et al*., 2011). These observations indicate an important role of maternal antioxidants in the development of the antioxidant system in the progeny and that maternal dietary vitamins can be applied to protect the progeny from oxidative injury. Vitamin D_3 and its metabolites are essential for calcium-phosphorus homeostasis and bone quality of poultry (Atencio *et al*., 2006; Driver *et al*., 2006). In the current study, progeny dietary high-vitamin premix increased serum calcium in ducklings. Our observations suggest the vitamin D_3 level recommended by the NRC (1994) as sufficient for proper tibia development in ducklings, as the higher levels of vitamin D_3 and 25-hydroxycholecalciferol in progeny high-vitamin premix did not affect tibia quality.

In conclusion, maternal dietary high-vitamin premix increased BW and tibia ash content in 1-day-old and serum T-SOD in 14-day-old progeny ducklings. Progeny dietary high-vitamin premix increased growth performance, antioxidant status, and serum calcium in ducklings. Growth of starter ducklings was interactively affected by maternal and progeny vitamin regimens.

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