

Effects of residual feed intake divergence on growth performance, carcass traits, meat quality, and blood biochemical parameters in small-sized meat ducks

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ABSTRACT Feed efficiency (**FE**) is a major economic trait of meat duck. This study aimed to evaluate the effects of residual feed intake (**RFI**) divergence on growth performance, carcass traits, meat quality, and blood biochemical parameters in small-sized meat ducks. A total of 500 healthy 21-day-old male ducks were housed in individual cages until slaughter at 63 d of age. The growth performance was determined for all the ducks. The carcass yield, meat quality, and blood biochemical parameters were determined for the selected 30 high-RFI (**HRFI**) and 30 low-RFI (**LRFI**) ducks. In terms of growth performance, the RFI, feed conversion ratio (**FCR**), and average daily feed intake (**ADFI**) were found to be significantly lower in the LRFI group ($P < 0.01$), whereas no differences were observed in the BW and body weight gain ($P > 0.05$). For slaughter performance, no differences were observed in the carcass traits between the LRFI and HRFI groups ($P > 0.05$). For meat quality, the shear force of breast muscle was

significantly lower in the LRFI group ($P < 0.05$), while the other meat quality traits of breast and thigh muscles demonstrated no differences ($P > 0.05$). For blood biochemical parameters, the serum concentrations of triglycerides (**TG**) and glucose (**GLU**) were significantly lower in the LRFI group ($P < 0.05$), while the other parameters showed no differences ($P > 0.05$). The correlation analysis demonstrated a high positive correlation between RFI, FCR, and ADFI ($P < 0.01$). The RFI demonstrated a negative effect on the breast muscle and lean meat yields, but a positive effect on the shear force of breast muscle ($P < 0.05$). Further, the RFI demonstrated a positive effect on the TG and GLU levels ($P < 0.05$). These results indicate that the selection for low RFI could improve the FE of small-sized meat ducks without affecting the production performance. This study provides valuable insight into the biological processes underlying the variations in FE in small-sized meat ducks.

Key words: small-sized meat duck, residual feed intake, production performance, correlation analysis

2022 Poultry Science 101:101990

<https://doi.org/10.1016/j.psj.2022.101990>

INTRODUCTION

China is a major producer of meat ducks, with an annual output of more than 4.1 billion, accounting for 68% of the global production in 2021 (Hou and Liu, 2022). In recent years, small-sized meat ducks have been well-received by consumers for their excellent meat quality, accounting for more than 15% of the total meat

duck production in China. However, low feed efficiency (**FE**) is currently a bottleneck in the production of small-sized meat ducks (Bai et al., 2020, 2022). It is well known that feed cost accounts for approximately 70% of the total production cost of meat ducks. FE is therefore an important economic factor in the production of meat ducks, the improvement of which reduces the feed requirement, production cost, and nitrogenous waste production (Zhang and Aggrey, 2003).

FE is generally defined as feed intake (**FI**) per unit of average daily gain (**ADG**), referred to as feed conversion ratio (**FCR**), which is well understood by farmers and is widely used. However, the ratio trait FCR is not normally distributed and does not account for the variability in growth and maintenance requirements.

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Received April 12, 2022.

Accepted May 29, 2022.

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Further, it is negatively correlated with several critical economic traits like BW and body weight gain (**BWG**). The genetic selection for FCR may therefore increase the BW and body size of livestock and poultry, leading to an increase in muscle fiber diameter and reduced meat quality (Lustrat et al., 2016). Hence, FCR is not an ideal measure to evaluate the FE of livestock and poultry, nor is it a suitable indicator for breeding small-sized meat ducks. Koch et al. (1963) proposed the concept of residual feed intake (**RFI**) which accounts for the differences between the actual FI and the expected feed requirements for the gain and maintenance of the BW. Genetic selection for RFI has been used to improve FE owing to its phenotypic independence of BW and BWG (Robinson and Oddy, 2004). Further, the Animal Genetic Resources Committee experts of the FAO suggested that the RFI-selection program could decrease FI and improve FE without affecting the production performance. RFI may therefore be a more sensitive and precise measure of FE. Previous studies have reported that approximately 35% of the genetic variation of FI can be evaluated by RFI (Cai et al., 2008), which is moderately heritable in poultry, ranging from 0.2 to 0.5 (Aggrey et al., 2010; Yuan et al., 2015; Begli et al., 2016; Zhang et al., 2017b). At present, a large number of breeders currently choose RFI instead of FCR for animal breeding. The genetic selection for RFI could have significant effects on the production performance of meat farm animals. Byerly et al. (1980) demonstrated that genetic selection for RFI can effectively improve FE in chickens. Wen et al. (2018) found that genetic selection for RFI can significantly reduce the FI and abdominal fat content without affecting BW and intramuscular fat content in broilers. Zhang et al. (2019) found that meat ducks with low RFI can effectively reduce feed costs and improve FE without affecting the carcass composition. However, very few studies have examined the effects of genetic selection to alter RFI on the production performance of small-sized meat ducks.

A series of our study focuses on rearing systems, breeding techniques, nutrient requirements, and FE of small-sized meat ducks. The objective of the present study was to evaluate the effects of RFI divergence on growth performance, carcass traits, meat quality, and blood biochemical parameters and their relationship in small-sized meat ducks. The findings provide valuable insight into the genetic selection for RFI in small-sized meat ducks.

MATERIALS AND METHODS

Experimental Design and Animal Husbandry

All the experimental procedures were conducted in strict accordance with the guidelines approved by the China Council on Animal Care and the Ministry of Science and Technology of the People's Republic of China. In addition, all experimental birds were managed and handled according to the guidelines approved by the Animal Care and Use Committee of Yangzhou

University (No.: SYDW-2019015). All efforts were made to minimize the suffering of the animals.

A total of 600 one-day-old male small-sized meat ducks (H strain) were procured from Ecolovo Group, China. All the ducks were raised on the floor (15 birds/m²) during the first 3 wk. Ducks with the highest and the lowest BW and those that were dead or had leg problems were excluded at 21 d of age (n = 100). The remaining 500 birds were then transferred to individual cages (73 cm × 55 cm × 80 cm) for the experiment, where feeders (20 cm × 10 cm × 10 cm) were set on one side of each cage. An overhead nipple drinking line was set in the middle of each cage (a nipple/bird). All the birds were raised contemporaneously in the same experimental facility until slaughter at 63 d of age. During the experimental period, all the birds had ad libitum access to feed and water and were reared on the same diet (Table 1) from 22 to 63 d of age.

Growth Performance

The initial BW was recorded at the beginning of the experiment (22nd d). At 63-days-old, the final BW and FI were recorded for each bird after starving them for 12 h. Growth performance parameters such as metabolic body weight (**MBW**^{0.75}), ADG, average daily feed intake (**ADFI**), and FCR were then calculated on d 63. The RFI was calculated following the method described by Aggrey et al. (2010). The equation used is provided as follows:

$$\text{RFI} = \text{FI} - (a + b_1 \times \text{MBW}^{0.75} + b_2 \times \text{ADG})$$

Table 1. Compositions and nutrients of the experimental diets.

Item	0–21 d	22–63 d
Ingredient (%)		
Corn	10.32	21.27
Wheat middling	15.41	20.00
Wheat bran	-	30.01
Rice noodles	35.21	10.00
Rice bran	15.81	5.00
Peanut meal	-	2.37
Soybean meal	12.63	2.50
Nucleotide slag	2.00	-
Limestone powder	1.52	1.96
Calcium hydrogen phosphate	1.10	0.89
Compound premix ¹	6.00	6.00
Total	100	100
Formulated nutrient profile (g/kg)		
Crude protein	210.00	140.00
Crude fat	20.00	35.00
Crude fiber	50.00	70.00
Crude ash	70.00	100.00
Calcium	10.00	10.00
Phosphorus	6.00	4.50
Sodium chloride	6.00	6.00
Methionine	4.00	2.80
Moisture	140.00	140.00

¹Supplied per kilogram of total diet: bentonite, 44.46 g; lysine, 3.24 g; DL-MHA-FA (88%), 0.99 g; threonine, 0.73 g; sodium chloride, 4.40 g; sodium bicarbonate, 2.00 g; sodium sulphate, 2.00 g; herbalife, 0.20 g; choline chloride (60%), 1.00 g; Jin Duowei, 0.53 g; Jin Yvkang, 0.15 g; C-811 enzyme, 0.30 g.

where a is the intercept, and b_1 and b_2 are the partial regression coefficients of FI on $MBW^{0.75}$ and ADG, respectively. The RFI values were calculated using the REG procedure in SAS (version 9.4, SAS Institute Inc., Cary, NC).

Carcass Characteristics

At the end of the experiment (63rd d), all the birds were sorted according to their RFI values. A total of 30 high-RFI (HRFI, $RFI \geq \text{mean} + 0.5 \text{ SD}$) and 30 low-RFI (LRFI, $RFI \leq \text{mean} - 0.5 \text{ SD}$) birds were finally selected to be weighed (live weight, LW) and slaughtered in the poultry processing plant. The weight of the defeathered carcass, which included the head and feet, was considered as carcass weight (CW). The carcass was then eviscerated manually and considered as semieviscerated weight (SEW) after the removal of the trachea, esophagus, gastrointestinal tract, crop, spleen, pancreas, gallbladder, and gonads. The head, feet, heart, liver, gizzard, glandular stomach, and abdominal fat were then removed and considered as the eviscerated weight (EW). Further, the carcass yield was determined as the percentage of LW. The breast muscle, thigh muscle, gizzard, and abdominal fat were separated and weighed, and their weights were defined as BMW, TMW, GW, and AFW, respectively. Further, the breast and thigh muscle yields were determined as the percentage of the EW. The lean meat percentage was determined as $(BMW+TMW)/EW$, the gizzard percentage was determined as $GW/(GW+EW)$, and the abdominal fat percentage was determined as $AFW/(AFW + EW)$, as per the standard proposed by the Ministry of Agriculture and Rural Affairs of the People's Republic of China (2020).

Meat Quality

The meat color, pH, water loss rate (WLR), and shear force were determined using the left side of the breast and thigh muscles. The color measures of the Commission Internationale de l'Eclairage, including lightness (L^*), redness (a^*), and yellowness (b^*) of the muscles were determined using a chroma-meter (CR-400, Konica Minolta, Tokyo, Japan) with a 65 light source and a 2° observer. The measurement was the average value of 3 readings. The pH value was obtained at 1 h (pH_1) and 24 h (pH_{24}), the muscle was stored for 24 h at 4°C postslaughter using a pH meter (pH-STAR, Matthaus, Berlin, Germany). The pH meter was calibrated with a pH 4.01 and 7.01 phosphate buffer before and during pH determinations. The average pH value was defined using 3 measurements. The WLR and shear force were determined using a meat quality pressure meter (Meat-1, Tenovo Food, Beijing, China) and a digital tenderness meter (C-LM3B, Tenovo Food, Beijing, China), respectively, following the methods of Liu et al. (2011) and Tang et al. (2009).

Blood Biochemical Parameters

After recording the BW and the remaining feed weight, approximately 5 mL of blood was collected from the brachial vein of the ducks from the LRFI and HRFI groups by venipuncture. The serum was separated using a refrigerated centrifuge at 3,000 rpm for 10 min at 4°C and stored at -80°C for biochemical parameters determination. The serum concentrations of insulin (INS), growth hormone (GH), adrenocorticotropic hormone (ACTH), cholecystokinin (CCK), cortisol (COR), ghrelin (GHR), and leptin (LEP) were determined using an enzyme immunoassay method with an automatic enzyme immunoassay analyzer (Diatek DR200BS, Wuxi, China) and commercial ELISA kits (Beijing Sino-UK Institute of Biological Technology, Beijing, China). The serum concentrations of the total cholesterol (TC), triglycerides (TG), high-density lipoprotein cholesterol (HDL-C), low-density lipoprotein cholesterol (LDL-C), glucose (GLU), creatine kinase (CK), and free fatty acid (FFA) were determined using a colorimetric method with an automatic biochemical analyzer (Hitachi 7080, Tokyo, Japan) and commercial kits (Biosino Bio-Technology and Science Incorporation, Beijing, China).

Statistical Analysis

The data were analyzed by one-way ANOVA using the GLM procedure in SAS (version 9.4, SAS Institute Inc., Cary, NC). Duncan's multiple comparison procedure was implemented to test the differences in the significance. Pearson's correlation was then performed to analyze the correlation between different phenotypes. Data were considered statistically significant when $P < 0.05$.

RESULTS AND DISCUSSION

Growth Performance

Table 2 presents the effects of RFI divergence on the growth performance. The ADFI of the ducks in the HRFI and LRFI groups were found to be 209.89 and 169.04 g per day, respectively. The FI of the birds in the

Table 2. Effects of RFI divergence on the growth performance of small-sized meat ducks from 22 to 63 d of age.

Items ¹	HRFI	LRFI	SEM	P-value
Initial BW (g)	627.00	657.00	14.504	0.309
Final BW (g)	2,175.07	2,191.73	37.029	0.826
$MBW^{0.75}$ (g)	318.22	320.11	4.064	0.821
ADG (g/d)	36.86	36.54	0.708	0.827
ADFI (g/d)	209.89 ^a	169.04 ^b	4.956	<0.001
FCR (g/g)	5.73 ^a	4.64 ^b	0.126	<0.001
RFI (g/d)	19.11 ^a	-22.70 ^b	4.392	<0.001

^{a,b}Within a row for each factor, different superscripts indicate significant differences ($P < 0.05$).

¹Initial BW, body weight on d 22; final BW, body weight on d 63; $MBW^{0.75}$, metabolic body weight on d 63; ADG, average daily gain; ADFI, average daily feed intake; FCR, feed conversion ratio; RFI, residual feed intake.

LRFI group was found to be approximately 19.5% less than that in the HRFI group ($P < 0.01$). It was therefore considered that the genetic selection for a low RFI is more beneficial for reducing feed costs. As expected, extremely significant differences ($P < 0.01$) were observed in the RFI and FCR between the LRFI (-22.70 and 4.64) and HRFI (19.11 and 5.73) groups, respectively. Importantly, no differences were observed in the initial BW, final BW, MBW^{0.75}, and ADG between the 2 groups ($P > 0.05$), which is in accordance with the results of high- and low-RFI mule ducks (Drouilhet et al., 2016b) and laying ducks (Zeng et al., 2017). Interestingly, similar results have been reported for several other farm animals, such as cattle (Lancaster et al., 2009), lambs (Zhang et al., 2017a), pigs (Young et al., 2011; Faure et al., 2013; Meunier-Salaün et al., 2014), rabbits (Drouilhet et al., 2016a), and chickens (Xu et al., 2016; Yi et al., 2018; Liu et al., 2019; Yang et al., 2020). Therefore, it was considered that a lower FI could satisfy the growth and maintenance requirements of the animals. Table 3 presents the Pearson correlation coefficients between RFI and growth performance. The results revealed that the RFI had a high positive correlation with FCR ($r = 0.78$, $P < 0.01$) and ADFI ($r = 0.63$, $P < 0.01$). However, no correlation was observed with the initial BW ($r = -0.10$, $P = 0.47$), final BW ($r = -0.07$, $P = 0.72$), MBW^{0.75} ($r = -0.07$, $P = 0.72$), and ADG ($r = -0.02$, $P = 0.93$), thereby supporting the results of the aforementioned comparisons of the growth performance traits between the HRFI and LRFI groups. These results are similar to what Zhang et al. (2017b), Yuan et al. (2015), and Yan et al. (2019) reported in Pekin ducks, laying chickens, and yellow broilers, respectively. Similarly, previous studies have confirmed that RFI is independent of BW and BWG in mammals (Rajaei Sharifabadi et al., 2016; Torres-Vázquez et al., 2018; Moraes et al., 2019). Considering the results of the current and previous studies, it may be believed that the selection for RFI can effectively reduce the FI and improve FE without affecting the BWG and marketing BW of small-sized meat ducks.

Carcass Characteristics

Table 4 demonstrates the effects of RFI divergence on the carcass characteristics. Slaughter performance is considered as an important measure of the economic

Table 4. Effects of RFI divergence on the carcass yield of small-sized meat ducks at 63 d of age.

Items ¹	HRFI	LRFI	SEM	P-value
Carcass yield (%)	82.05	81.51	0.373	0.480
Semi-eviscerated yield (%)	76.66	76.04	0.387	0.429
Eviscerated yield (%)	70.28	69.48	0.410	0.339
Breast muscle yield (%)	14.02	14.73	0.197	0.071
Thigh muscle yield (%)	11.76	11.88	0.261	0.830
Lean meat yield (%)	25.78	26.61	0.316	0.091
Gizzard yield (%)	3.94	4.11	0.099	0.394
Abdominal fat yield (%)	2.22	2.16	0.086	0.725

¹Carcass yield, % = carcass weight/live weight \times 100; eviscerated yield, % = eviscerated weight/live weight \times 100; semieviscerated yield, % = semi-eviscerated weight/live weight \times 100; breast muscle yield, % = breast muscle weight/eviscerated weight \times 100; thigh muscle yield, % = thigh muscle weight/eviscerated weight \times 100; lean meat yield, % = (breast muscle weight + thigh muscle weight)/eviscerated weight \times 100; gizzard yield, % = gizzard weight/(gizzard weight + eviscerated weight) \times 100; abdominal fat yield, % = abdominal fat weight/(abdominal fat weight + eviscerated weight) \times 100.

profit of meat farm animals. In this study, the yields of the defeathered, semieviscerated, and eviscerated carcass were above 81%, 76%, and 69%, respectively, which is in accordance with the results of our previous study (Bai et al., 2022). Interestingly, low RFI did not significantly affect the slaughter performance, including the yields of the defeathered, semieviscerated, eviscerated carcass, breast muscle, thigh muscle, lean meat, gizzard, and abdominal fat ($P > 0.05$). The results were consistent with the majority of the carcass characteristics reported by Drouilhet et al. (2014), except that the muscle weight was significantly higher in low-RFI Muscovy ducks. Lefaucheur et al. (2011) found that pigs with low RFI had leaner carcasses with higher muscle content, lower backfat thickness, and lower intramuscular fat content, indicating that selection for low RFI affected pig muscle mass. Although the small-sized meat ducks in the LRFI group had a slightly higher muscle yield, it was not significant ($P > 0.05$), which also indicates the advantages of low RFI ducks. Notably, abdominal fat is a waste of fat deposition in animals, a reduction of which may reduce the total production costs. Zhang et al. (2017a) revealed that sheep with a lower RFI had a lower FI and less fat deposition. Wen et al. (2018) found that genetic selection for RFI can significantly reduce the FI and abdominal fat content in broilers. The results of the current study revealed that LRFI ducks had slightly lower abdominal fat deposits than HRFI ducks. However, this difference was not

Table 3. Pearson correlation coefficients between RFI and growth performance.

	Initial BW	Final BW	MBW ^{0.75}	ADG	ADFI	FCR	RFI
Initial BW	1						
Final BW	0.65**	1					
MBW ^{0.75}	0.65**	1.00**	1				
ADG	0.32*	0.80**	0.80**	1			
ADFI	0.20	0.46**	0.46**	0.48**	1		
FCR	-0.04	-0.35*	-0.35*	-0.40*	0.48**	1	
RFI	-0.10	-0.07	-0.07	-0.02	0.63**	0.78**	1

*Indicates a significant correlation ($P < 0.05$).

**Indicates an extremely significant correlation ($P < 0.01$).

significant ($P > 0.05$) and was similar to what Zhang et al. (2019) reported in Pekin ducks. Table 5 demonstrates the Pearson correlation coefficients between RFI and carcass yield. The results revealed that RFI had a moderate negative correlation with breast muscle yield ($r = -0.39$, $P < 0.05$) and lean meat yield ($r = -0.45$, $P < 0.05$), while RFI had a weak or no correlation with other carcass compositions ($P > 0.05$). Arthur et al. (2001) found a positive correlation between RFI and ultrasound backfat measures in pigs, where a lower RFI resulted in thinner backfat. Gilbert et al. (2012) reported that a low RFI in growing pigs is correlated with reduced fat and FI. Similarly, several studies on cattle have shown that RFI has a positive correlation with body fat content (Richardson et al., 2001; Basarab et al., 2003; Schenkel et al., 2004). Therefore, considering the results obtained in this study and previous studies, it may be considered that small-sized meat ducks with low RFI can be useful in improving FE without affecting the carcass composition.

Meat Quality

Table 6 presents the effects of RFI divergence on meat quality. Meat quality is essential for meat consumption and is generally reflected by several traditional characteristics, such as meat color, pH, drip loss, and shear force. The L^* and a^* values of the breast and thigh muscles were slightly higher and lower, respectively, indicating that duck meat with low RFI was brighter and lighter. Moreover, WLR is generally employed to measure the water-holding capacity, where a decrease is associated with the loss of nutrients and flavor. In this study, the results demonstrated that the WLR of ducks was slightly higher in the LRFI group, suggesting lower water-holding capacity. Generally, a higher L^* value, lower a^* value, and higher drip loss represent poor meat quality (Bai et al., 2022). Fortunately, there were almost no differences in the traits of breast and thigh muscles between the HRFI and LRFI small-sized meat ducks ($P > 0.05$), which is in accordance with the results of high-, medium-, and low-RFI chickens (Yang et al., 2020), and efficient- and inefficient-RFI cattle (Nascimento et al., 2016). Smith et al. (2011) also indicated that the selection for low RFI can improve carcass composition and has few effects on the pH and water-holding capacity of fresh pork. Therefore, in the production of meat duck, the pursuit of excessively low FI can reduce the total production costs and improve the FE but likely impair the meat quality. Notably, tenderness is considered the most important quality of meat and is defined by shear force. Here, the shear force of the breast and thigh muscles in the LRFI group was lower than that in the HRFI group, which was significant in the breast muscle ($P < 0.05$), indicating tender muscle and better meat quality. Table 7 presents the Pearson correlation coefficients between RFI and meat quality. Interestingly, RFI had a moderate positive correlation with the shear force of breast muscle ($r = 0.36$, $P < 0.05$), whereas there was

Table 5. Pearson correlation coefficients between RFI and carcass yield.

	Carcass yield	Semiveiscerated yield	Eviscerated yield	Breast muscle yield	Thigh muscle yield	Lean meat yield	Gizzard yield	Abdominal fat yield	FCR	RFI
Carcass yield	1									
Semiveiscerated yield	0.83**	1								
Eviscerated yield	0.83**	0.97**	1							
Breast muscle yield	-0.16	-0.06	-0.10	1						
Thigh muscle yield	-0.16	-0.17	-0.15	0.30	1					
Lean meat yield	-0.16	-0.13	-0.13	0.62**	0.57**	1				
Gizzard yield	-0.21	-0.18	-0.32*	0.13	0.13	0.19	1			
Abdominal fat yield	-0.20	-0.32	-0.47*	0.17	-0.08	-0.10	-0.18	1		
FCR	0.03	0.08	0.11	-0.41*	-0.12	-0.36*	-0.16	0.18	1	
RFI	0.07	0.13	0.14	-0.39*	-0.15	-0.45*	-0.18	0.14	0.78**	1

*Indicates a significant correlation ($P < 0.05$.)

**Indicates an extremely significant correlation ($P < 0.01$.)

Table 6. Effects of RFI divergence on the meat quality of small-sized meat ducks at 63 d of age.

Items	RFI group	Meat color ¹			pH ²		Water loss rate ³ (%)	Shear force (N)
		L*	a*	b*	pH ₁	pH ₂₄		
Breast muscle	HRFI	39.29	14.82	4.76	5.83	5.81	45.72	14.30 ^a
	LRFI	40.28	14.64	4.77	5.77	5.81	48.92	9.56 ^b
	SEM	0.733	0.345	0.180	0.025	0.026	0.903	1.253
	<i>P</i> -value	0.509	0.801	0.968	0.240	0.980	0.345	0.005
Thigh muscle	HRFI	38.74	15.92	7.28	6.69	6.69	36.82	20.49
	LRFI	39.59	14.60	7.07	6.63	6.70	38.53	19.46
	SEM	0.841	0.684	0.455	0.023	0.031	0.959	1.305
	<i>P</i> -value	0.622	0.342	0.819	0.190	0.909	0.602	0.520

^{a,b}Within a column for each factor, different superscripts indicate significant differences ($P < 0.05$).

¹L*, lightness; a*, redness; b*, yellowness.

²pH₁, pH value measured 1 h after slaughter; pH₂₄, pH value measured 24 h after slaughter.

³Water loss rate, % = $(W_{\text{Initial}} - W_{\text{Final}}) / W_{\text{Initial}} \times 100$.

Table 7. Pearson correlation coefficients between RFI and meat quality.

Items		L*	a*	b*	pH ₁	pH ₂₄	Water loss rate	Shear force	FCR	RFI
Breast muscle	L*	1								
	a*	-0.51**	1							
	b*	0.18	0.03	1						
	pH ₁	0.10	-0.22	0.25	1					
	pH ₂₄	0.26	-0.33	0.05	0.53**	1				
	Water loss rate	0.12	0.13	-0.10	-0.08	0.04	1			
	Shear force	0.18	-0.11	0.09	0.23	0.31	-0.17	1		
	FCR	-0.10	-0.07	-0.05	0.12	-0.09	-0.21	0.37*	1	
	RFI	-0.04	-0.006	-0.005	0.10	-0.06	-0.27	0.36*	0.78**	1
	Thigh muscle	L*	1							
a*		-0.59**	1							
b*		-0.45*	0.49**	1						
pH ₁		-0.19	0.27	0.16	1					
pH ₂₄		-0.06	0.001	-0.19	0.41*	1				
Water loss rate		0.02	-0.01	0.03	-0.29	-0.23	1			
Shear force		-0.16	0.33	0.38*	0.17	-0.32	-0.24	1		
FCR		-0.04	0.03	-0.15	0.10	-0.07	-0.24	0.17	1	
RFI		-0.05	0.07	-0.09	0.21	-0.04	-0.25	0.18	0.78**	1

*Indicates a significant correlation ($P < 0.05$).

**Indicates an extremely significant correlation ($P < 0.01$).

Table 8. Effects of RFI divergence on the blood biochemical parameters of small-sized meat ducks at 63 d of age.

Items ¹	HRFI	LRFI	SEM	<i>P</i> -value
INS (uIU/mL)	10.20	10.47	0.315	0.673
GH (ng/mL)	5.42	5.27	0.171	0.677
ACTH (pg/mL)	23.41	20.98	0.830	0.145
COR (ng/mL)	5.39	4.85	0.225	0.235
CCK (pmol/L)	2.99	3.14	0.100	0.467
GHR (ng/mL)	77.11	76.85	3.380	0.274
LEP (ng/mL)	6.52	6.44	0.098	0.681
TC (mmol/L)	5.92	5.56	0.128	0.155
TG (mmol/L)	0.92 ^a	0.74 ^b	0.037	0.013
HDL-C (mmol/L)	2.78	2.91	0.056	0.245
LDL-C (mmol/L)	1.74	1.70	0.057	0.755
GLU (mmol/L)	8.56 ^a	7.52 ^b	0.194	0.005
CK (U/L)	1,348.96	1,326.57	66.666	0.870
FFA (mmol/L)	0.90	0.94	0.038	0.744

^{a,b}Within a column for each factor, different superscripts indicate significant differences ($P < 0.05$).

¹Abbreviations: ACTH, adrenocorticotropic hormone; CCK, cholecystokinin; CK, creatine kinase; COR, cortisol; FFA, free fatty acid; GH, growth hormone; GHR, ghrelin; GLU, glucose; HDL-C, high-density lipoprotein cholesterol; INS, insulin; LDL-C, low-density lipoprotein cholesterol; LEP, leptin; TC, total cholesterol; TG, triglycerides.

no significant correlation between RFI and other meat quality traits ($P > 0.05$). These results indicate that selection for low RFI may not affect meat quality, which is in agreement with several previous studies on chickens

(Wen et al., 2018; Yang et al., 2020) and cattle (Fidelis et al., 2017). Therefore, considering the results of this study as well as previous studies, it is logical to assume that an appropriate reduction of FI can maintain most of the meat quality of small-sized meat ducks.

Blood Biochemical Parameters

Table 8 demonstrates the effects of RFI divergence on the blood biochemical parameters. Interestingly, the ducks in the LRFI group had lower serum concentrations of TG and GLU than those in the HRFI group ($P < 0.05$), which is similar to the results of high- and low-RFI small-sized meat ducks detected at 42 d of age (not published) and consistent with the results of high- and low-RFI pigs (Rauw et al., 2007). However, the data in this study were not in agreement with several previous studies. Lombardi et al. (2022), Jorge-Smeding et al. (2021), and (Leão et al., 2021) reported no differences in the GLU content between high- and low-RFI farm animals. Yang et al. (2020) and Horodyska et al. (2019) observed higher levels of TG and GLU in animals with high FE. These contradictory results may be explained by the differences in the experimental environment, animal breed, physiology, and blood collection time. It is well known

Table 9. Pearson correlation coefficients between RFI and blood biochemical parameters.

	INS	GH	ACTH	COR	CCK	GHR	LEP	TC	TG	HDL-C	LDL-C	GLU	CK	FFA	FCR	RFI
INS	1															
GH	0.35*	1														
ACTH	-0.09	-0.51**	1													
COR	-0.37*	-0.71**	0.52**	1												
CCK	0.10	0.11	-0.44*	-0.34*	1											
GHR	0.48*	0.52**	-0.14	-0.57**	-0.62**	1										
LEP	-0.005	0.08	0.23	-0.19	-0.12	0.46*	1									
TC	0.04	0.01	0.01	0.003	-0.03	0.36*	0.07	1								
TG	0.31	-0.09	-0.10	0.18	-0.03	0.01	-0.06	0.02	1							
HDL-C	-0.19	-0.14	-0.14	-0.04	0.03	-0.06	-0.02	0.13	-0.22	1						
LDL-C	0.18	0.16	0.07	0.07	-0.17	0.27	-0.08	0.69**	0.07	-0.20	1					
GLU	-0.03	0.15	-0.24	-0.23	-0.14	0.12	-0.05	-0.13	-0.08	0.21	-0.06	1				
CK	-0.30	-0.01	-0.31	-0.08	-0.08	-0.03	-0.08	0.21	0.003	0.16	0.16	0.39*	1			
FFA	0.08	-0.17	0.09	0.19	0.17	0.11	0.14	0.41*	0.22	-0.09	0.23	-0.15	-0.21	1		
FCR	-0.001	0.29	0.18	0.20	-0.15	0.22	0.004	0.07	0.38*	-0.05	0.05	0.32*	0.16	-0.20	1	
RFI	-0.11	0.25	0.28	0.20	-0.11	0.10	0.003	0.22	0.42*	-0.12	0.07	0.34*	0.07	-0.02	0.78**	1

*Indicates a significant correlation ($P < 0.05$).

**Indicates an extremely significant correlation ($P < 0.01$).

that ACTH is released into the circulation and acts on peripheral areas, mainly the adrenal glands, to stimulate the production of glucocorticoids and strictly regulates the production of COR (Novoselova et al., 2019). In this study, the ACTH and COR contents of LRFI ducks were lower than those of HRFI ducks. However, the differences were not significant ($P > 0.05$). Similarly, previous studies have demonstrated lower ACTH concentrations in low-RFI chickens (Yang et al., 2020) and lambs (Zhang et al., 2017a). LEP is primarily produced by adipose tissue and is known to regulate BW and FI. It has been reported to be associated with decreased FE and increased fatness (Hoque et al., 2009). Brown et al. (2004) found that the LEP concentration was not related to FI or FE, which is similar to the findings of this study. The other 2 important hormones, CCK and GHR, are closely related to animal appetite. CCK, which is also found in the brain, is a hormone secreted by the duodenal mucosa that regulates the emptying of the gallbladder and the secretion of enzymes by the pancreas. Several previous studies have revealed that CCK plays an important regulatory role in feeding behavior, especially in inhibiting animal FI (Richards, 2003; Gibbs et al., 2012). GHR is an acylated peptide that stimulates GH release from the pituitary gland. Several previous studies have revealed that GHR is a physiological mediator of appetite and possibly plays a role in growth regulation by stimulating appetite and GH release, which is opposite to the effect of CCK (Nakazato et al., 2001; Blevins et al., 2002). In the current study, the CCK and GHR contents in the LRFI ducks were higher and lower, respectively, than those of HRFI ducks. However, the differences were not significant ($P > 0.05$). Table 9 demonstrates the Pearson correlation coefficients between RFI and blood biochemical parameters. The results revealed that RFI had a moderate positive correlation with TG ($r = 0.42$, $P < 0.05$) and GLU ($r = 0.34$, $P < 0.05$). There was no significant correlation between RFI and the other blood biochemical parameters ($P > 0.05$). It should be noted that according to the actual functions and relationships of several serum biochemical parameters aforementioned, the current data confirmed

that the ACTH content had a high positive correlation with the COR content ($r = 0.52$, $P < 0.01$), and the GHR content had a high positive correlation with GH content ($r = 0.52$, $P < 0.01$) and a high negative correlation with CCK content ($r = -0.62$, $P < 0.01$). Therefore, considering the results obtained in this study as well as previous studies, it is logical to assume that an appropriate reduction of FI can maintain the health status of small-sized meat ducks.

In summary, the findings confirm the enormous potential for improving the FE of small-sized meat ducks. Moreover, the results suggest that the selection for low RFI is beneficial in improving the FE of small-sized meat ducks without affecting their BWG, marketing BW, carcass composition, and meat quality. The present study provides valuable insight into the biological processes underlying the variations in FE of small-sized meat ducks and provides a theoretical basis for the application of RFI in duck breeding.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (31902140) and the China Agriculture Research System (CARS-42). We would like to thank Editage (www.editage.cn) for English language editing.

DISCLOSURES

The authors declare that they have no competing interests.

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