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Original article

The effects of genotype and overfeeding on fat level and composition of adipose and muscle tissues in ducks

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Abstract – This study was conducted to evaluate the effects of genotype (Muscovy, Pekin and their crossbred hinny and mule ducks) and overfeeding (14 days from 12 weeks of age) on the quantity and quality of lipid deposition in adipose and muscle tissue in ducks. Samples of muscles (*Pectoralis major* and *Iliotibialis superficialis*) and abdominal fat were collected at 14 weeks of age to determine lipid levels, lipid classes and fatty acid composition. By comparison with the other genotypes, Pekin ducks exhibited higher amounts of abdominal fat and higher lipid levels in muscles (+105 and +120% in *P. major* and *Iliotibialis superficialis*, respectively) by comparison with Muscovy ducks. By comparison with other genotypes, Muscovy ducks exhibited the lowest triglyceride and phospholipid levels in muscles and Pekin ducks the highest levels. Muscovy ducks also showed the lowest cholesterol levels in *I. Superficialis* muscles. Muscovy ducks exhibited the highest levels of saturated fatty acids (SFA) and poly-unsaturated fatty acids (PUFA) in muscle and adipose tissues and the lowest levels of mono-unsaturated fatty acids (MUFA), and Pekin ducks exhibited the reverse. For all these parameters, the crossbred ducks always presented intermediate values. Overfeeding induced an accumulation of lipids in adipose and muscle tissues (1.2- to 1.7-fold, depending on muscle type and genotype). This increase was higher in *P. major* than in *I. superficialis* muscles. The increase in the amount of abdominal fat was 1.7- to 3.1-fold, depending on genotype. This increase in lipid levels in peripheral tissues was mainly induced by triglyceride deposition. Finally, it induced a considerable increase in proportions of MUFA (particularly oleic acid) (expressed as % of total fatty acids) at the expense of PUFA (particularly arachidonic acid) and SFA. However, the amounts (expressed as g per 100 g of tissue) of SFA and MUFA increased in tissues while the amounts of PUFA remained unchanged in muscles and decreased in abdominal fat. The quantity and quality of fat deposition in peripheral tissues depends on the liver's ability to synthesise and also to export lipids.

lipids / fatty acids / meat / muscles / ducks

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Résumé – Influence du génotype et du gavage sur la teneur en lipides des tissus adipeux et musculaires de canards. Cette étude avait pour objectif d'évaluer les effets du génotype (Barbarie, Pékin et leurs croisements, hinny et mulard) et du gavage (14 jours à partir de l'âge de 12 semaines) sur la quantité et la qualité des lipides déposés dans le tissu adipeux et les muscles de canards. Des échantillons de muscle (*Pectoralis major* et *Iliotibialis superficialis*) et de gras abdominal ont été collectés à l'âge de 14 semaines afin de déterminer leur teneur en lipides, les classes de lipides et la composition en acides gras. Par comparaison avec les autres génotypes, les canards Pékin avaient plus de gras abdominal et une quantité de lipides intramusculaires plus élevée (+105 et +120 % dans le *P. major* et l'*Iliotibialis superficialis*, respectivement par comparaison avec le canard de Barbarie). Par comparaison avec les autres génotypes, les canards de Barbarie présentaient les teneurs en triglycérides et phospholipides dans les muscles les plus faibles et les canards Pékin les plus élevées. La teneur en cholestérol de l'*Iliotibialis superficialis* était également plus faible chez les canards de Barbarie. Dans les muscles et les tissus adipeux, les canards de Barbarie présentaient les proportions d'acides gras saturés (AGS) et poly-insaturés (AGPI) les plus élevées et le pourcentage d'acides gras mono-insaturés (AGMI) le plus faible. La situation inverse était observée chez les canards Pékin. Pour tous ces paramètres, les canards hinnies et mulards présentaient des valeurs intermédiaires. Le gavage a induit une accumulation de lipides dans les tissus adipeux et musculaires : multiplié par 1,2 à 1,7 selon le muscle et le génotype. Cette augmentation était plus importante dans le *P. major* que dans l'*Iliotibialis superficialis*. La quantité de gras abdominal a été multipliée par 1,7 à 3,1 selon le génotype. Cette augmentation de la teneur en lipides des tissus périphériques a surtout été induite par un dépôt de triglycérides. Enfin, le gavage accroît le pourcentage (exprimé en % des AG totaux) d'AGMI (en particulier l'acide oléique) au détriment des AGPI (en particulier l'acide arachidonique) et des AGS. Cependant, les quantités (exprimées en g par 100 g de tissu) d'AGS et d'AGMI augmentent dans les tissus alors que celle des AGPI reste stable dans les muscles et décroît dans le gras abdominal. La quantité et la qualité des lipides déposés dans les tissus périphériques dépendent donc de l'aptitude du foie à les synthétiser mais également à les exporter.

lipides / acides gras / viande / muscles / canards

1. INTRODUCTION

Intramuscular fat (IMF) is involved in determining meat quality, particularly the nutritional and sensory characteristics and storage ability [16]. Lipid levels in duck meat are higher than in chicken and turkey meat and depend on the species, age, sex and nutrition [3]. Moreover, in Pekin and Muscovy ducks, selection for low abdominal fat also decreases lipid levels in muscles [4, 22], but this type of selection has no effect on IMF in broiler chickens [24]. By comparison with lean Muscovy ducks, lipid levels of breast meat were found to be twice as high in overfed Muscovy ducks [28]. Depending on the source of energy in the diet (starch and lipids) the fatty acid profile of IMF in poultry reflects a balance between hepatic lipogenesis and dietary lipids [21]. In birds, lipids are mainly synthesised in the liver and then exported to peripheral tissues, including the muscles [18]. Guy et al. [13] and Hermier et al. [14] showed that different duck genotypes (Pekin, Muscovy and their crossbred hinny and mule ducks) present different susceptibilities to storing lipids in the liver and in peripheral tissues such as adipose tissues and muscles during an overfeeding period. Pekin ducks show more marked extra-hepatic fattening (higher amounts of abdominal and subcutaneous fat) and Muscovy ducks exhibit the opposite. It therefore seemed interesting to use these different duck genotypes in combination with feeding levels (ad libitum vs. overfeeding) to analyse more precisely the consequences of hepatic export ability on lipid quantity and quality (lipid classes and fatty acid profiles) deposited in muscles and abdominal fat.

2. MATERIALS AND METHODS

2.1. Animals and diets

We used male ducks from four different genotypes: Pekin, Muscovy and their crossbred mule (male Muscovy duck × female Pekin duck) and hinny ducks (male Pekin duck × female Muscovy duck). The ducks (50 per genotype) originated from the same sires and dams provided by the Grimaud Company (Roussay, France). They were reared under natural light and temperature conditions at the Experimental Station for Waterfowl Breeding (INRA Artiguères, France), distributed at one genotype per pen. They were fed ad libitum from hatching to 6 weeks of age. From 6 to 12 weeks of age, the birds were fed on a restricted diet at levels appropriate to the ingestion ability of each genotype (200–250 g per duck at the beginning, increasing to 360–380 g at the end of the period). At 12 weeks of age, 35 ducks per genotype were overfed at the maximum of their ingestion potential for 14 days with corn and corn meal (Tab. I). During the overfeeding period, 12 ducks per genotype were fed with the growing diet ad libitum (controls). The composition and main characteristics of the diets (starting, growing and overfeeding) are shown in Tables I and II. The overfeeding diet had lower protein levels, higher lipid levels and higher levels of metabolisable energy than the growing diet. The differences in fatty acid composition were small.

2.2. Growth and overfeeding performance

Growth rate and feed conversion ratio were evaluated by the individual weighing of animals and measuring food consumption per genotype (n = 1) at 4, 6 and 12 weeks of age. At 14 weeks of age, 8 ducks per genotype and dietary treatment chosen at random were weighed and sacrificed by sectioning of the neck. Immediately after bleeding, *Pectoralis major* (a breast muscle), *Iliotibialis superficialis* (a thigh muscle), liver and abdominal fat were excised and weighed. The samples of adipose and muscle tissues were frozen and stored at –20 °C.

The present study was carried out in agreement with the French legislation on animal experimentation and with authorisation from the French Ministry of Agriculture (Animal Health and Protection Directorate).

2.3. Chemical analysis

Moisture and mineral levels in the diets were determined with the oven method [2], and protein levels with the Kjeldahl copper catalyst method [2]. Total lipids were extracted quantitatively from diets and tissues, by homogenising samples of minced tissue in chloroform/methanol 2/1 v/v and collecting gravimetrically [9]. The classes of lipids were determined using Iatroscan (Iatron, Tokyo, Japan) with 10 silica-gel thin layer chromatography rods and a flame ionisation detector system (TLC-FID) according to Mares et al. [19]. The hydrogen flow rate was 160 mL per min, the air flow rate 2 L per min and scanning speed 0.3 cm per s. The software used (Boreal, JMBS Development, Grenoble, France) recorded chromatograms and integrated peaks with reference to an external standard (Sigma, St Quentin Fallavier, France). The fatty acid composition was determined after transmethylation of lipids [20] by gas chromatography (Perkin Elmer Autosystem, St Quentin en Yvelines, France). Injector and detector (FID) temperatures were 250 °C, the carrier gas was nitrogen with a head column pressure of 16.5 psi using a capillary column (25 m × 0.22 mm, BPX70, SGE, Villeneuve St Georges, France).

Table I. Composition and characteristics of feed for rearing and overfeeding periods. The preparation for overfeeding contained corn (25%), corn meal (35%) and water (40%).

Composition (g per kg)	Starting (0–4 weeks)	Growing (4–12 weeks)	Overfeeding (12–14 weeks)
Wheat	200.00	254.50	
Wheat starch			2.90
Corn	357.02	370.48	988.49
Sorghum		80.00	
Triticale	100.00		
Extruded soybean seeds	40.00	15.00	
Rapeseed oilmeal solvent extracted	30.00	50.00	
Soybean meal	184.75	138.75	
Sunflower meal	29.00	44.50	
Sugarcane molasses	20.00	15.00	
Calcium carbonate	13.50	10.00	
Dicalcium phosphate	17.75	15.00	
Sodium chloride	1.00	1.75	1.45
Sodium bicarbonate	2.50	1.50	1.45
DL-methionine	1.88	1.12	
Choline-HCl 75%	0.60	0.40	
Vitamin and mineral supplement	2.00[1]	2.00[1]	5.71[2]
Characteristics (g per kg)*			
Metabolisable Energy (MJ per kg)	11.83	11.68	13.92
Crude proteins	175.10	160.00	82.46
Total lipids	30.40	27.40	37.36
Lysine	9.20	7.80	–
Sulphur amino acids	7.70	7.10	–
Calcium	11.0	9.00	–
Available phosphorus	4.50	4.00	–

* Calculated values.

[1] Supplied per kilogram of diet: 9 000 IU vitamin A; 1 500 IU cholecalciferol; 22 mg vitamin E; 2 mg vitamin K_3; 1 mg vitamin B_1; 85 mg Mn; 80 mg Zn; 30 mg Fe; 15 mg Cu.

[2] Supplied per kilogram of diet: 3.48 mg vitamin E; 34.22 mg Mn; 29.58 mg Zn; 17.40 mg Fe; 4.64 mg Cu; 1.16 mg I.

Methyl esters were identified and quantified by comparison with standards (Sigma, St Quentin Fallavier, France).

2.4. Statistical analysis

Data were analysed by analysis of variance using the SAS General Linear Model procedure [27]. The model included the main effects of genotype, feeding plan and their interaction. Significant differences between means were shown in the different groups according to the Newman-Keul test.

3. RESULTS

3.1. Feed consumption, growth performance and body composition of ducks

Muscovy ducks displayed the lowest feed conversion ratios and consumption

Table II. Chemical composition of feed for rearing and overfeeding periods. The preparation for overfeeding contained corn (25%), corn meal (35%) and water (40%).

Composition (%)	Starting (0–4 weeks)	Growing (4–12 weeks)	Overfeeding (12–14 weeks)
Dry matter	89.86	89.21	89.25
Crude protein	18.21	15.98	8.28
Minerals	5.92	5.03	1.57
Total lipids	3.34	2.84	3.38
Triglycerides*	76.68	77.18	89.01
Cholesterol*	5.72	4.97	3.37
Phospholipids*	17.60	17.83	7.62
Σ SFA**	17.17	16.10	14.52
C16:0	12.31	12.55	11.56
C18:0	3.06	2.37	2.03
C20:0	1.03	1.18	0.94
C22:0	0.77	nd	nd
Σ MUFA**	24.98	28.36	27.43
C18:1 n-9	24.98	28.36	27.43
Σ PUFA**	57.85	55.54	58.03
C18:2 n-6	54.24	53.32	56.80
C18:3 n-3	3.61	2.22	1.23
PUFA+MUFA/SFA	4.82	5.21	5.89

SFA, MUFA, PUFA = Saturated, Mono-Unsaturated and Poly-Unsatured Fatty Acids.
* = Expressed as % of total lipids. ** = Expressed as % of total fatty acids
nd = not detected.

Table III. The effects of duck genotype on feed conversion ratio (FCR, kg of feed/kg of weight gain) during the rearing period (0 to 12 weeks), total feed consumption of equivalent dry maize (g) during the overfeeding period (12 to 14 weeks), total feed consumption (g) of control ducks during the same period (n = 1) and body weight (BW, g) during the rearing period (mean ± SEM, n = 50).

Periods	Muscovy	Hinny	Mule	Pekin
FCR during the rearing period	2.76	3.23	3.29	3.63
Total consumption of overfeeding diet	8219	10341	10552	9674
Total consumption of growing diet	3112	4027	4295	3923
BW at 4 weeks	1257 ± 92 d	1593 ± 85 c	1684 ± 115 b	1741 ± 124 a
BW at 6 weeks	2715 ± 148 c	2626 ± 148 d	2846 ± 209 b	2985 ± 183 a
BW at 12 weeks	4919 ± 323 a	4588 ± 395 b	4622 ± 314 b	4477 ± 294 b

a–d: Significant difference between genotypes for one parameter, $P < 0.05$.

of maize or growing diet during the rearing and overfeeding periods, respectively (Tab. III). Pekin ducks had the highest feed conversion ratios during the rearing period. Mule ducks displayed the highest ingestion capacity during the overfeeding period.

By comparison with the other genotypes, Muscovy ducks exhibited the lowest body weights at 4 weeks of age, and the highest at 12 and 14 weeks of age (Tabs. III, IV). Between 4 and 14 weeks of age, body weights of control Muscovy

Table IV. The effects of genotype and overfeeding on body weight (g), weight (g) of liver, muscles (*P. major* and *I. superficialis*) and abdominal fat, total lipid, triglyceride, cholesterol and phospholipid levels (g per 100 g of tissue) in *P. major* and *I. superficialis* muscles and abdominal fat in 14-week-old ducks (means ± SEM – n = 8).

Fatty acids	Muscovy		Hinny		Mule		Pekin		Genotype	Overfeeding
	Overfed	Control	Overfed	Control	Overfed	Control	Overfed	Control	effect	effect
Body weight	6393 ± 441 a	5418 ± 245 b	6315 ± 402 a	4854 ± 497 c	6473 ± 351 a	4455 ± 392 c	5999 ± 353 a	4623 ± 426 c	***	***
Liver weight	467 ± 90 a	77 ± 7 c	495 ± 85 a	61 ± 6 c	494 ± 97 a	61 ± 13 c	318 ± 75 b	56 ± 11 c	***	***
P. major										
Weight	408 ± 49	398 ± 39	290 ± 25	297 ± 29	309 ± 28	278 ± 30	208 ± 33	216 ± 18	***	ns
Total lipids	3.65 ± 0.51	2.26 ± 0.36	5.92 ± 0.98	3.87 ± 1.44	5.24 ± 0.96	3.13 ± 0.54	7.57 ± 0.85	4.59 ± 0.68	***	***
Triglycerides	2.37 ± 0.47 d	1.02 ± 0.24 e	4.35 ± 0.76 b	2.19 ± 0.87 d	3.66 ± 0.91 c	1.79 ± 0.32 d	5.95 ± 0.86 a	3.09 ± 0.58 c	***	***
Cholesterol	0.13 ± 0.05	0.12 ± 0.04	0.14 ± 0.05	0.16 ± 0.08	0.16 ± 0.04	0.13 ± 0.03	0.15 ± 0.02	0.17 ± 0.03	ns	ns
Phospholipids	1.15 ± 0.17	1.13 ± 0.10	1.43 ± 0.26	1.53 ± 0.51	1.42 ± 0.11	1.21 ± 0.24	1.46 ± 0.13	1.33 ± 0.15	**	ns
I. superficialis										
Weight	30.09 ± 3.26	32.82 ± 4.37	23.01 ± 2.51	22.93 ± 3.55	23.06 ± 3.08	22.34 ± 2.46	19.00 ± 1.63	19.48 ± 2.79	***	ns
Total lipids	2.52 ± 0.61	2.16 ± 0.29	3.99 ± 0.97	3.16 ± 0.61	3.74 ± 0.61	2.79 ± 0.39	5.73 ± 0.76	4.55 ± 0.54	***	***
Triglycerides	1.54 ± 0.48	1.30 ± 0.32	2.75 ± 0.82	2.12 ± 0.56	2.55 ± 0.56	1.88 ± 0.30	4.20 ± 0.68	3.39 ± 0.51	***	***
Cholesterol	0.11 ± 0.02	0.12 ± 0.02	0.14 ± 0.03	0.13 ± 0.03	0.14 ± 0.01	0.11 ± 0.01	0.17 ± 0.04	0.15 ± 0.04	***	ns
Phospholipids	0.87 ± 0.19	0.73 ± 0.08	1.10 ± 0.16	0.90 ± 0.07	1.05 ± 0.12	0.80 ± 0.11	1.35 ± 0.18	1.00 ± 0.07	***	***
Abdominal fat										
Weight	220 ± 23	109 ± 20	256 ± 27	107 ± 35	224 ± 42	73 ± 35	265 ± 22	155 ± 29	***	***
Total lipids	94.60 ± 3.22	89.00 ± 9.14	93.23 ± 4.02	91.89 ± 4.55	90.98 ± 10.61	89.39 ± 5.84	96.88 ± 3.23	91.35 ± 4.12	ns	*
Triglycerides	93.80 ± 3.12	87.75 ± 9.20	92.00 ± 3.92	90.46 ± 4.41	90.03 ± 10.43	88.02 ± 5.90	95.87 ± 3.09	89.00 ± 4.92	ns	**
Cholesterol	0.44 ± 0.15	0.59 ± 0.15	0.93 ± 0.22	0.74 ± 0.22	0.60 ± 0.24	0.65 ± 0.25	0.62 ± 0.33	1.74 ± 2.06	ns	ns
Phospholipids	0.36 ± 0.25	0.65 ± 0.41	0.30 ± 0.26	0.68 ± 0.38	0.35 ± 0.15	0.72 ± 0.75	0.39 ± 0.14	0.61 ± 0.41	ns	**

*, **, ***: Significant effect, $P < 0.05$, $P < 0.01$, $P < 0.001$; ns = non significant.

a–e: Significant difference between groups for one criterion, $P < 0.05$ (interaction between genotype and overfeeding).

ducks were 4.3 times higher whereas they were 2.6 to 3.0 times higher for the other genotypes.

By comparison with other genotypes, Pekin ducks had the lowest liver weights. Muscovy ducks had the highest muscle weights (Tab. IV).

By comparison with control ducks, overfeeding induced a significant increase in body (+30%), liver (7-fold) and abdominal fat (2.2-fold) weights but had no effect on muscle weight (Tab. IV). The increase in body weight was about 45% for mule ducks, 30% for hinny and Pekin ducks and 18% for Muscovy ducks. Liver weight was 8.1 times higher for mule and hinny ducks, 6.1 times higher for Muscovy ducks and 5.7 times higher for Pekin ducks.

3.2. Lipid levels and composition in muscle and adipose tissues

By comparison with other genotypes, Muscovy ducks exhibited the lowest lipid, triglyceride and phospholipid levels in muscles and Pekin ducks the highest levels of lipids and triglycerides (Tab. IV). Pekin ducks had the highest cholesterol levels in *I. superficialis* muscle. In *P. major* muscle, the cholesterol levels were similar for all genotypes. Triglyceride and phospholipid levels were lower in *I. superficialis* than in *P. major* muscles (calculated average of 2.47 vs. 3.05 and 0.98 vs. 1.33 g per 100 g of muscle) and cholesterol levels were similar (calculated average of 0.14 g per 100 g of muscle). Genotype had no significant effect on lipid levels or lipid classes in abdominal fat (Tab. IV). Abdominal fat had 30 times more triglycerides than breast muscle (calculated average of 91 vs. 3 g per 100 g of tissue) and 6 times more cholesterol (calculated average of 0.79 vs. 0.14 g per 100 g of tissue). By contrast, phospholipid levels were lower (calculated average of 0.51 vs. 1.33 g per 100 g of tissue).

Overfeeding induced a significant increase in lipid levels of *P. major* (1.6-fold) and *I. superficialis* muscles (1.3-fold) and a slight increase in the amount of abdominal fat (+4%, Tab. IV). Triglyceride levels only increased in the *P. major* muscle (2.0-fold, Tab. IV). Triglyceride and phospholipid levels were higher in overfed ducks than in control ducks in *I. superficialis* muscle (+27% for both lipid classes, Tab. IV). Overfeeding induced a significant increase in triglyceride levels (+4.6%) to the detriment of phospholipid levels in abdominal fat (Tab. IV).

The main fatty acids in muscle and adipose tissues were C16:0 (23–25%) and C18:0 (7–10%) (saturated fatty acids, SFA), C18:1 n-9 (40–52%) and C16:1 n-7 (3–4%) (mono-unsaturated fatty acids, MUFA), C18:2 n-6 (12–13%) and C20:4 n-6 (4–5%) (poly-unsaturated fatty acids, PUFA, Tabs. V–VII). This latter was not detected in abdominal fat (Tab. VII). Muscles and fatty tissues contained high proportions of n-6 fatty acids and very low proportions of n-3 fatty acids. *I. superficialis* muscle had higher proportions of MUFA and lower proportions of SFA and PUFA than the *P. major* muscle (Tab. VI). Abdominal fat had higher proportions of MUFA and lower proportions of PUFA than muscle tissues. Overall Pekin ducks exhibited the highest proportions of MUFA and the lowest proportions of SFA and PUFA in all tissues analysed (Tabs. V–VII). Muscovy ducks exhibited the highest proportions of SFA and PUFA and the lowest proportions of MUFA.

In all tissues, overfeeding induced an increase in the proportions of MUFA and a decrease in the proportions of PUFA (Tabs. V–VII). The increase in the proportions of SFA was only significant in *I. superficialis* muscle and abdominal fat. Calculating the amounts of fatty acids per 100 g of tissue showed that overfeeding finally induced large increases in SFA and MUFA levels in all tissues (Fig. 1).

Table V. The effects of genotype and overfeeding on fatty acid composition (% of total fatty acids) of total lipids in *P. major* muscle in 14-week-old ducks (means ± SEM – n = 8).

Fatty acids	Muscovy		Hinny		Mule		Pekin		Genotype	Overfeeding
	Overfed	Control	Overfed	Control	Overfed	Control	Overfed	Control	effect	effect
C13 : 0	0.22 ± 0.30 b	1.48 ± 1.00 a	0.05 ± 0.15 b	0.32 ± 0.35 b	0.16 ± 0.23 b	0.47 ± 0.56 b	0.11 ± 0.19 b	0.40 ± 0.27 b	***	***
C14 : 0	0.49 ± 0.36	0.43 ± 0.66	0.37 ± 0.15	0.14 ± 0.25	0.44 ± 0.05	0.41 ± 0.62	0.35 ± 0.15	0.46 ± 0.34	ns	ns
C16 : 0	26.25 ± 1.08	24.19 ± 2.37	25.66 ± 1.61	24.40 ± 2.34	26.08 ± 1.07	24.97 ± 1.94	23.24 ± 0.84	23.40 ± 1.08	**	*
C17 : 0	nd	0.12 ± 0.35	nd	nd	nd	0.13 ± 0.37	nd	nd	ns	ns
C18 : 0	10.06 ± 0.84 ab	11.21 ± 1.41 a	9.75 ± 0.71 b	9.40 ± 1.44 b	10.39 ± 0.94 ab	9.71 ± 1.16 b	9.22 ± 0.64 b	7.46 ± 0.78 c	***	ns
C20 : 0	nd	0.17 ± 0.34	nd	nd	nd	0.26 ± 0.57	nd	nd	ns	ns
C24 : 0	0.95 ± 0.11	1.60 ± 0.88	0.57 ± 0.08	1.09 ± 0.17	0.83 ± 0.28	0.96 ± 0.81	0.49 ± 0.04	0.72 ± 0.30	**	**
Σ SFA	37.97 ± 1.22	39.20 ± 1.59	36.40 ± 1.80	35.35 ± 3.31	37.91 ± 1.19	36.92 ± 1.82	33.39 ± 1.31	32.42 ± 1.15	***	ns
C15 : 1 n-5	1.29 ± 0.65 c	3.21 ± 0.60 a	0.86 ± 0.19 cd	1.82 ± 0.41 b	1.24 ± 0.28 c	2.11 ± 0.64 b	0.60 ± 0.12 d	1.09 ± 0.28 cd	***	***
C16 : 1 n-7	3.10 ± 0.24 b	2.47 ± 0.76 c	3.20 ± 0.25 b	3.24 ± 0.49 b	3.25 ± 0.33 b	3.29 ± 0.88 b	3.60 ± 0.36 b	4.18 ± 0.61 a	***	ns
C17 : 1 n-7	0.53 ± 0.12	0.62 ± 0.57	0.44 ± 0.05	0.42 ± 0.47	0.56 ± 0.08	0.38 ± 0.43	0.40 ± 0.04	0.40 ± 0.25	ns	ns
C18 : 1 n-9	41.37 ± 2.03 b	30.58 ± 2.07 d	43.89 ± 2.66 b	37.38 ± 3.79 c	40.60 ± 1.02 b	36.06 ± 3.10 c	46.58 ± 2.10 a	43.51 ± 2.17 b	***	***
C20 : 1 n-9	0.06 ± 0.18	0.31 ± 0.60	0.13 ± 0.24	nd	nd	0.37 ± 0.70	0.44 ± 0.19	0.08 ± 0.22	ns	ns
Σ MUFA	46.35 ± 1.61 c	37.20 ± 2.24 e	48.52 ± 2.61 bc	42.86 ± 3.42 d	45.66 ± 0.92 c	42.22 ± 3.18 d	51.62 ± 1.79 a	49.26 ± 2.25 ab	***	***
C18 : 2 n-6	11.62 ± 0.82 d	16.04 ± 1.02 a	11.26 ± 0.50 d	15.47 ± 0.95 ab	11.71 ± 0.78 d	14.59 ± 1.43 b	11.30 ± 0.70 d	13.49 ± 0.83 c	***	***
C18 : 3 n-3	0.08 ± 0.16	0.30 ± 0.65	0.33 ± 0.14	0.31 ± 0.34	0.20 ± 0.21	0.33 ± 0.72	0.46 ± 0.04	0.64 ± 0.35	ns	ns
C20 : 3 n-6	0.29 ± 0.34	nd	0.33 ± 0.23	nd	0.34 ± 0.24	0.19 ± 0.54	0.55 ± 0.17	0.05 ± 0.13	ns	*
C20 : 4 n-6	3.70 ± 0.60 cd	7.26 ± 1.42 a	3.15 ± 0.50 cd	6.02 ± 0.98 b	4.18 ± 0.61 c	5.75 ± 1.75 b	2.68 ± 0.37 d	4.14 ± 1.11 c	***	***
Σ PUFA	15.69 ± 1.39 d	23.60 ± 1.86 a	15.08 ± 1.00 d	21.80 ± 1.26 b	16.43 ± 1.32 d	20.86 ± 3.27 b	14.99 ± 1.03 d	18.32 ± 1.77 c	***	***
MUFA/SFA	1.64 ± 0.09	1.55 ± 0.10	1.75 ± 0.15	1.85 ± 0.29	1.64 ± 0.08	1.71 ± 0.12	2.00 ± 0.12	2.09 ± 0.11	***	ns
PUFA/SFA	0.41 ± 0.04	0.60 ± 0.06	0.41± 0.02	0.62 ± 0.07	0.44 ± 0.05	0.57 ± 0.10	0.45 ± 0.03	0.56 ± 0.05	ns	***
Σ n-6	15.60 ± 1.45 cd	23.30 ± 1.95 a	14.75 ± 0.97 d	21.49 ± 1.40 b	16.23 ± 1.41 cd	20.53 ± 3.06 b	14.53 ± 1.00 d	17.68 ± 1.82 c	***	***
Σ n-3	0.08 ± 0.16	0.30 ± 0.65	0.33 ± 0.14	0.31 ± 0.34	0.20 ± 0.21	0.33 ± 0.72	0.46 ± 0.04	0.64 ± 0.35	ns	ns

*, **, ***: Significant effect, $P < 0.05$, $P < 0.01$, $P < 0.001$; ns = non significant; nd = not detected.
a–d: Significant difference between groups for one criterion, $P < 0.05$ (interaction between genotype and overfeeding).
SFA, MUFA, PUFA = Saturated, Mono-Unsaturated and Poly-Unsatured Fatty Acids.

Table VI. The effects of genotype and overfeeding on fatty acid composition (% of total fatty acids) of total lipids in *I. superficialis* muscle in 14-week-old ducks (means ± SEM – n = 8).

Fatty acids	Muscovy		Hinny		Mule		Pekin		Genotype	Overfeeding
	Overfed	Control	Overfed	Control	Overfed	Control	Overfed	Control	effect	effect
C13 : 0	1.91 ± 0.86	0.72 ± 1.01	1.14 ± 0.28	0.14 ± 0.34	1.01 ± 0.35	0.16 ± 0.34	1.05 ± 0.45	0.23 ± 0.37	**	***
C14 : 0	0.15 ± 0.27	0.07 ± 0.19	0.44 ± 0.27	0.13 ± 0.21	0.28 ± 0.30	0.08 ± 0.17	0.17 ± 0.24	0.12 ± 0.19	ns	**
C16 : 0	23.76 ± 1.03	23.43 ± 1.88	23.75 ± 0.60	23.16 ± 0.69	23.61 ± 1.19	23.11 ± 0.30	21.00 ± 0.65	21.05 ± 0.87	***	ns
C18 : 0	10.37 ± 1.37 ab	11.14 ± 1.11 a	10.29 ± 1.17 ab	9.77 ± 1.35 ab	9.57 ± 0.93 b	9.06 ± 0.63 b	9.20 ± 1.11 b	7.30 ± 0.52 c	***	*
C20 : 0	nd	1.07 ± 1.27 a	nd	0.30 ± 0.49 b	nd	0.41 ± 0.44 b	nd	0.07 ± 0.17 b	*	***
Σ SFA	36.19 ± 1.19	36.44 ± 2.85	35.61 ± 1.39	33.49 ± 1.82	34.46 ± 1.16	32.82 ± 0.46	31.43 ± 1.53	28.77 ± 1.28	***	***
C15 : 1 n-5	2.21 ± 0.52	2.56 ± 0.83	1.03 ± 0.22	1.60 ± 0.29	1.23 ± 0.27	1.54 ± 0.29	0.30 ± 0.35	0.84 ± 0.18	***	***
C16 : 1 n-7	4.03 ± 0.29 b	3.12 ± 0.26 c	4.36 ± 0.44 ab	3.84 ± 0.39 b	4.66 ± 0.42 a	4.19 ± 0.24 ab	4.20 ± 0.39 ab	4.61 ± 0.55 a	***	***
C17 : 1 n-7	0.07 ± 0.19	0.08 ± 0.24	nd	0.31 ± 0.37	0.26 ± 0.28	0.44 ± 0.30	0.06 ± 0.18	nd	**	ns
C18 : 1 n-9	41.08 ± 1.74	39.53 ± 2.52	44.27 ± 1.59	41.95 ± 1.41	44.17 ± 1.08	42.27 ± 2.56	50.33 ± 1.39	49.28 ± 1.88	***	***
C20 : 1 n-9	0.07 ± 0.19	0.16 ± 0.44	nd	nd	nd	nd	0.11 ± 0.21	nd	ns	ns
Σ MUFA	47.45 ± 1.51	45.46 ± 2.17	49.66 ± 1.63	47.71 ± 1.22	50.31 ± 0.94	48.43 ± 2.22	55.00 ± 1.49	54.73 ± 1.96	***	***
C18 : 2 n-6	12.07 ± 0.77	13.63 ± 2.31	11.75 ± 0.59	14.41 ± 0.79	11.81 ± 0.75	14.61 ± 1.12	11.21 ± 0.40	13.11 ± 0.79	*	***
C18 : 3 n-3	nd	0.14 ± 0.25	nd	0.26 ± 0.31	0.06 ± 0.16	0.38 ± 0.25	0.11 ± 0.20	0.33 ± 0.29	ns	***
C20 : 4 n-6	4.29 ± 0.93	4.35 ± 1.55	2.97 ± 0.49	4.12 ± 0.86	3.37 ± 0.81	3.75 ± 0.73	2.25 ± 0.41	3.06 ± 0.83	***	**
Σ PUFA	16.36 ± 1.50	18.11 ± 3.71	14.72 ± 0.84	18.80 ± 0.96	15.23 ± 1.36	18.75 ± 1.92	13.57 ± 0.53	16.50 ± 1.33	**	***
MUFA/SFA	1.77 ± 0.09 d	1.76 ± 0.21 d	1.81 ± 0.11 c	1.99 ± 0.15 c	1.91 ± 0.09 cd	2.05 ± 0.04 c	2.19 ± 0.16 b	2.48 ± 0.16 a	***	***
PUFA/SFA	0.45 ± 0.05	0.50 ± 0.13	0.41 ± 0.03	0.56 ± 0.05	0.44 ± 0.05	0.57 ± 0.06	0.43 ± 0.03	0.57 ± 0.05	ns	***
Σ n-6	16.36 ± 1.50	17.97 ± 3.65	14.72 ± 0.84	18.53 ± 0.76	15.18 ± 1.40	18.36 ± 1.78	13.46 ± 0.53	16.17 ± 1.53	**	***
Σ n-3	nd	0.14 ± 0.25	nd	0.26 ± 0.31	0.06 ± 0.16	0.38 ± 0.25	0.11 ± 0.20	0.33 ± 0.29	ns	***

*, **, ***: Significant effect, $P < 0.05$, $P < 0.01$, $P < 0.001$; ns = non significant; nd = not detected.
a–d: Significant difference between groups for one criterion, $P < 0.05$ (interaction between genotype and overfeeding).
SFA, MUFA, PUFA = Saturated, Mono-Unsaturated and Poly-Unsatured Fatty Acids.

Table VII. The effects of genotype and overfeeding on fatty acid composition (% of total fatty acids) of total lipids in abdominal fat of 14-week-old ducks (means ± SEM – n = 8).

Fatty acids	Muscovy		Hinny		Mule		Pekin		Genotype	Overfeeding
	Overfed	Control	Overfed	Control	Overfed	Control	Overfed	Control	effect	effect
C13 : 0	0.60 ± 0.14	0.53 ± 0.09	0.55 ± 0.18	0.52 ± 0.13	0.49 ± 0.10	0.57 ± 0.14	0.54 ± 0.14	0.55 ± 0.10	ns	ns
C14 : 0	0.58 ± 0.04	0.50 ± 0.06	0.53 ± 0.06	0.48 ± 0.06	0.53 ± 0.06	0.47 ± 0.02	0.41 ± 0.04	0.38 ± 0.04	***	***
C16 : 0	26.48 ± 1.57	25.37 ± 0.77	26.79 ± 3.18	24.63 ± 1.18	25.14 ± 1.04	24.82 ± 1.60	21.94 ± 1.44	21.01 ± 1.53	***	**
C18 : 0	7.80 ± 0.41 b	7.14 ± 0.55 b	9.27 ± 2.55 a	6.68 ± 0.91 b	7.33 ± 0.32 b	6.82 ± 1.29 b	7.25 ± 1.51 b	4.96 ± 0.55 c	***	***
C20 : 0	0.03 ± 0.08	0.17 ± 0.14	nd	0.08 ± 0.22	nd	0.06 ± 0.11	nd	0.04 ± 0.12	ns	*
Σ SFA	35.49 ± 1.62	33.60 ± 1.02	37.15 ± 5.57	32.37 ± 1.85	33.49 ± 1.33	32.74 ± 2.25	30.17 ± 2.84	26.94 ± 1.85	***	***
C16 : 1 n-7	3.56 ± 0.27 b	3.03 ± 0.35 ab	3.23 ± 0.43 ab	3.28 ± 0.43 ab	3.64 ± 0.18 ab	3.26 ± 0.65 ab	3.42 ± 0.54 ab	3.82 ± 0.52 a	ns	ns
C18 : 1 n-9	48.38 ± 2.04	45.36 ± 1.34	48.44 ± 4.65	48.02 ± 1.15	50.95 ± 1.50	46.98 ± 1.90	55.20 ± 2.14	55.08 ± 2.18	***	**
C20 : 1 n-9	0.13 ± 0.15	0.22 ± 0.14	0.14 ± 0.15	0.31 ± 0.13	0.25 ± 0.16	0.37 ± 0.06	0.36 ± 0.15	0.45 ± 0.05	***	***
Σ MUFA	52.07 ± 1.94 bc	48.62 ± 1.46 c	51.81 ± 5.01 bc	51.62 ± 1.15 bc	54.84 ± 1.74 b	50.60 ± 2.26 c	58.98 ± 2.55 a	59.35 ± 1.99 a	***	**
C18 : 2 n-6	12.03 ± 1.03 d	17.03 ± 0.92 a	10.82 ± 0.73 de	15.39 ± 1.17 b	11.29 ± 1.00 de	16.03 ± 1.59 ab	10.52 ± 0.55 e	13.17 ± 0.94 c	***	***
C18 : 3 n-3	0.42 ± 0.06	0.75 ± 0.05	0.23 ± 0.19	0.62 ± 0.09	0.38 ± 0.05	0.63 ± 0.06	0.33 ± 0.14	0.55 ± 0.13	***	***
Σ PUFA	12.44 ± 1.08 d	17.77 ± 0.95 a	11.05 ± 0.79 e	16.01 ± 1.22 b	11.67 ± 1.05 de	16.66 ± 1.60 b	10.85 ± 0.62 e	13.72 ± 1.04 c	***	***
MUFA/SFA	1.82 ± 0.13	1.98 ± 0.09	1.74 ± 0.36	2.10 ± 0.18	1.99 ± 0.12	2.07 ± 0.20	2.34 ± 0.32	2.73 ± 0.26	***	***
PUFA/SFA	0.35 ± 0.03	0.53 ± 0.03	0.31 ± 0.06	0.50 ± 0.06	0.35 ± 0.03	0.51 ± 0.06	0.36 ± 0.05	0.51 ± 0.05	ns	***
Σ n-6	12.03 ± 1.03 d	17.03 ± 0.92 a	10.82 ± 0.73 de	15.39 ± 1.17 b	11.29 ± 1.00 de	16.03 ± 1.59 ab	10.52 ± 0.55 e	13.17 ± 0.94 c	***	***
Σ n-3	0.42 ± 0.06	0.75 ± 0.05	0.23 ± 0.19	0.62 ± 0.09	0.38 ± 0.05	0.63 ± 0.06	0.33 ± 0.14	0.55 ± 0.13	***	***

*, **, ***: Significant effect, $P < 0.05$, $P < 0.01$, $P < 0.001$; ns = non significant; nd = not detected.
a–e: Significant difference between groups for one criterion, $P < 0.05$ (interaction between genotype and overfeeding).
SFA, MUFA, PUFA = Saturated, Mono-Unsaturated and Poly-Unsatured Fatty Acids.

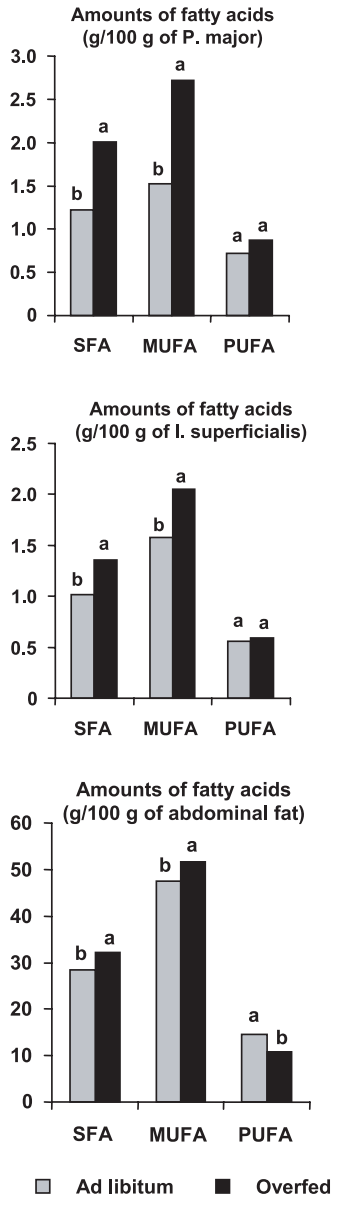

Figure 1. The effects of feeding level on the amounts of saturated, mono-unsaturated and poly-unsaturated fatty acids (SFA, MUFA, PUFA) in *P. major* and *I. superficialis* muscles and abdominal fat of 14-week-old ducks (n = 32).
a, b: Significant difference between overfed and ad libitum fed ducks, $P < 0.05$.

PUFA levels remained unchanged in muscle tissues and decreased in abdominal fat (Fig. 1). Overfeeding had greater effects in *P. major* than in *I. superficialis* muscle and abdominal fat. Finally, we found significant negative correlations between proportions of PUFA and total lipid levels in muscles (–0.66 and –0.58 for *P. major* and *I. superficialis* muscles, respectively).

4. DISCUSSION

Lean Muscovy ducks exhibited the lowest feed conversion ratios during the rearing and overfeeding periods, and Pekin ducks the highest. Broiler chickens selected for low abdominal fat also had better feed conversion ratios than chickens selected for high abdominal fat [1]. This characteristic could suggest that, as in chickens selected for low abdominal fat, Muscovy ducks fed ad libitum were leaner than Pekin ducks because of lower lipogenesis activity.

During the overfeeding period, mule and hinny ducks ingested the highest amounts of feed and Muscovy ducks the lowest. This observation confirmed the previous results of Guy et al. [12, 13]. The ingestion ability of mule and hinny ducks benefits from a heterosis effect and this could partly explain their ability to produce large fatty livers. Indeed, when the amount of feed during the overfeeding period was adjusted to body weight, mule ducks produced smaller fatty livers than Muscovy ducks [8]. In spite of lower feed consumption, Muscovy ducks were able to produce heavy fatty livers. This genotype is therefore efficient in using nutrients for lipid synthesis when overfed.

By comparison with the other genotypes, Muscovy ducks displayed later body and muscle development but higher growth potential, as previously reported by Ricard [25]. At 14 weeks of age, they exhibited the highest body weight, the highest muscle

weight and the lowest fattiness, and for these reasons this species has been chosen for the production of duck meat in France [25]. By contrast, the Pekin duck is characterised by early body development. Their adipose tissues are therefore probably developed earlier (adipocyte hypertrophy induced by lipid deposition), and when compared at the same age Pekin ducks have higher carcass fattiness and higher IMF than Muscovy ducks. The difference in muscle weight between Muscovy ducks and the other genotypes (+63% and +90% for *I. superficialis* and *P. major* muscles, respectively, by comparison with Pekin ducks) could be partly explained by higher cross-sectional area of muscle fibres (measured by Chartrin et al. [7] on the same birds), and also by a higher number and/or length of muscle fibres.

By comparison with other genotypes, Pekin ducks exhibited smaller fatty livers but greater amounts of abdominal fat and higher lipid levels in muscles (+105 and +120% in *P. major* and *Iliotibialis superficialis* muscles, respectively, by comparison with Muscovy ducks). Guy et al. [13] and Hermier et al. [14] showed that Pekin ducks also display higher levels of subcutaneous adipose tissue than Muscovy ducks. Pekin ducks seem therefore to have greater hepatic ability to export neo-synthesised lipids and this could influence the quality of lipids deposited in peripheral tissues.

We found higher levels of triglycerides and cholesterol in *P. major* muscles of lean Muscovy ducks than Salichon et al. [26], but in our study, the ducks were sacrificed two weeks later. For lean mule ducks, we found equivalent levels to those obtained by Baéza et al. [5]. The quantity of phospholipids was higher in muscles than in abdominal fatty tissue, which contains smaller amounts of cellular membranes. By comparison with other genotypes, Muscovy ducks exhibited the lowest triglyceride and phospholipid levels in muscles and Pekin ducks the highest levels. Muscovy ducks also had the lowest cholesterol levels in *I. superficialis* muscle. Muscovy ducks displaying greater fibre size for a given amount of muscle [7] have a smaller total sarcolemma perimeter and therefore lower structural lipid levels (phospholipids) than the other genotypes.

The diets in the present study contained a high level of carbohydrates (about 600 g of starch per kg of overfeeding diet), which favours hepatic lipogenesis [17]. By comparison with other genotypes, Muscovy ducks exhibited the highest proportions of SFA and PUFA and the lowest proportions of MUFA and Pekin ducks displayed the reverse in muscles and adipose tissues. Birds mainly synthesise MUFA such as oleic and palmitoleic acids [15]. Our results suggest that Pekin ducks accumulate more MUFA and SFA in peripheral tissues than the other genotypes, particularly Muscovy ducks (3.08 and 2.00 vs. 1.27 and 1.14 g per 100 g of *P. major*).

Overfeeding induced a considerable increase in body weight. This resulted from a dramatic increase in the synthesis of lipids in the liver, accumulated first in the liver and also in peripheral tissues such as adipose tissues and muscles [13, 14]. The lipid levels of muscles increased accordingly (1.2 to 1.7-fold depending on muscle type and genotype). This increase was greater in *P. major* than in *I. superficialis* muscle which had completed its development before the overfeeding period. The increase in the quantity of abdominal fat was 1.7 to 3.1 times greater depending on the genotype. This increase in lipid levels in peripheral tissues mainly resulted from triglyceride deposition. Finally, overfeeding induced a considerable increase in the amounts of MUFA (particularly oleic acid) and SFA, while the amounts of PUFA remained unchanged in the muscles and decreased in abdominal fat. This result was consistent with those of Girard et al. [11] and Zanusso et al. [28]. Ducks ingest a large quantity of

carbohydrates (corn) during overfeeding, inducing intense hepatic lipogenesis. The neo-synthesised MUFA are then exported and accumulated in peripheral tissues. The effects of overfeeding on fatty acid composition of muscles are also consistent with the defective incorporation of linoleic acid and linoleic- and linolenic-derived PUFA observed, despite the high proportion of these essential fatty acids in an overfeeding diet based on corn [6]. These authors concluded that de novo hepatic lipogenesis prevails over dietary lipid intake in overfed waterfowl, affecting lipid composition of tissues. Gabarrou et al. [10] also suggested lower $\Delta 5$ and $\Delta 6$ desaturase activity. Finally, we confirmed the negative correlation between proportions of PUFA and total lipid levels in muscles previously reported by Rabot [23] in the chicken.

Overfeeding had no significant effect on the muscle weight. It has already been demonstrated that muscle growth is reduced or stopped during overfeeding [13].

5. CONCLUSION

From a dietary point of view, duck meat has a high proportion of unsaturated fatty acids but a low proportion of n-3 fatty acids. Increasing IMF resulted in decreased levels of n-3 and n-6 fatty acids. By combining genotype and overfeeding effects, we were able to obtain a wide range of lipid levels in muscles (from 2.26 to 7.57 in *P. major* and from 2.16 to 5.73 in *I. superficialis*). Muscovy ducks displayed the lowest intramuscular lipid, triglyceride and MUFA levels and Pekin ducks the highest. Overfeeding induced a considerable increase in lipid, triglyceride, SFA and MUFA levels in muscles and exacerbated the difference observed between lean Pekin and Muscovy ducks in terms of IMF levels. Except for body weights and the weights of fatty livers, the crossbred hinny and mule ducks always showed values intermediate between those of the parental genotypes for all the criteria measured in this study.

These differences in lipid levels and composition might also influence meat quality (tenderness, juiciness, colour, flavour) and storage ability (lipid oxidation and rancidity) from a sensory point of view and this needs further investigation.

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