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DIETARY PROTEIN-TO-CARBOHYDRATE RATIO AFFECTS DEVELOPMENT AND METABOLISM IN *DROSOPHILA* LARVAE AND IMAGO

Nadya Stefanyshyn [1], ***Olha Strilbytska*** [1], ***Nadia Burdyliuk*** [1], ***Olena Zadorozhna*** [2], ***Volodymyr Bubalo*** [3], ***Ihor Yurkevych*** [1], ***Oleh Lushchak*** [1,4]

[1] *Vasyl Stefanyk Precarpathian National University 57 Shevchenko St., Ivano-Frankivsk 76000, Ukraine*

[2] *Uman State Pedagogical University named after Pavlo Tychyna 2 Sadova St., Cherkasy region, Uman 20300, Ukraine*

[3] *L. I. Medved's Research Center of Preventive Toxicology, Food and Chemical Safety, Ministry of Health, SE, 6 Heroiv Oborony St., Kyiv 03680, Ukraine*

[4] *Research and Development University, 13A Shota Rustaveli St., Ivano-Frankivsk 76018, Ukraine*

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Background. Nutrition during growth and development affects various traits not only in larvae but also imago including lifespan, reproduction, feeding, metabolism, and stress resistance. In this study, we have tested the hypothesis of whether the dietary protein-to-carbohydrate (P:C) ratio in the developmental diet could be related to subsequent changes in metabolic profile and physiological parameters in *Drosophila* larvae and imago.

Materials and Methods. *Drosophila melanogaster Canton-S* strain were used in this study. Larvae were fed diets with different P:C ratios. Experimental media were composed of either 2 % or 5 % dry yeast and 0 %, 1 %, or 10 % of sucrose. We tested developmental rate, wet or dry body weight and the levels of certain metabolites including glucose, glycogen, triacylglycerides and total lipids. The developmental rate was assessed by counting the number of generated pupae every 6/6/12 hours. For wet or dry weight measurement, 20 larvae or flies were weighed and transferred to plastic vial with a cut bottom. The flies were dried at 60 °C with the subsequent weighing after two days. Another two-day flies cohort were separated by sex and frozen in liquid nitrogen

for further biochemical assays. Hemolymph glucose, total lipid concentration, triacylglycerides (TAG), body glucose and glycogen contents were determined spectrophotometrically.

Results. We found that a low 0.08 P:C ratio in the diet slowed down pupation by ~20 % and decreased body weight in larvae. Hemolymph glucose levels in both larvae and imago were inversely associated with dietary P:C. Larvae developing on a diet with a low P:C ratio displayed a lower level of glycogen pool, but a higher level of lipids. Developmental dietary P:C ratio also influences metabolic traits such as hemolymph glucose, glycogen, TAG and total lipids in male and female imago. A higher total protein intake combined with restriction of sucrose consumption had glucose-lowering and lipids-lowering effects.

Conclusions. Our study demonstrated that nutritional conditions during larval development trigger adaptive changes that provide a level of regulation necessary to surpass dietary stress in *Drosophila* imago.

Keywords: development, nutrition, macronutrients, calories, fruit fly

INTRODUCTION

Developmental diet contributes to long-term changes in the structure and functions of certain organs, as well as the homeostasis of metabolic pathways, programming the state of health (Vaiserman *et al.*, 2018). The mechanism of metabolic programming is mediated by epigenetic changes, such as DNA methylation and histone modifications, both involving chromatin remodeling (Zhu *et al.*, 2019).

The fruit fly *Drosophila melanogaster* has become an excellent model organism in nutrition research and developmental biology. Numerous studies on *Drosophila* have shown that early developmental nutritional conditions have significant consequences for adult physiology and metabolism (Klepsatel *et al.*, 2020; Strilbytska *et al.*, 2022). Larvae diet exerts a long-term influence upon the adult production of toxic molecules – autotoxins, that influence the lifespan (Stefana *et al.*, 2017). Evolutionarily conserved TOR and insulin signaling pathways (ISP) have been shown as major factors mediating the nutrient-dependent regulation of physiological and metabolic traits (Semaniuk *et al.*, 2021; Lushchak *et al.*, 2017; Semaniuk *et al.*, 2021).

Previous studies have reported that variation in dietary P:C balance by altering the concentrations of yeast and sugar in the diet has a significant impact on the lifespan of *Drosophila* (Lee *et al.*, 2008; Lushchak *et al.*, 2012; Bruce *et al.*, 2013). Moreover, we previously have shown that the parental dietary P:C ratio influenced the lifespan, reproduction, appetite and metabolism of offspring with strong associations between traits in two generations. Here, we show, that the balance between protein and carbohydrate, known as protein-to-carbohydrate ratio (P:C) of the developmental diet directly affects carbohydrate metabolism, fat accumulation and body weight of both *Drosophila* larvae and imago.

MATERIALS AND METHODS

Insects, maintaining and conditions. Wild-type *Canton-S D. melanogaster* flies were used in all experiments (Bloomington Stock Center, Indiana University, USA). Flies were reared in 250 mL glass bottles with 25 mL of yeast-corn-molasses medium

containing 7.5 % of molasses, 5 % of dry yeast, 6.1 % of corn, and 1 % of agar with the supplementation of 0.18 % nipagin as an anti-fungal agent. Flies were kept at 25 °C, 55–60 % humidity in a 12-h dark/light cycle.

Experimental procedures. Flies aged 3–7 days were subjected to 3-hour starvation with a subsequent 15-hour egg-laying on a medium composed of 5 % sucrose and 2 % agar. To prevent effects caused by larval density, the laid eggs were washed three times with distilled water, concentrated, and 150–200 eggs were transferred into glass bottles containing 25 ml of experimental medium. Experimental food contained dry yeast (in concentrations of 2% or 5%), sucrose (in concentrations of 0%, 1%, or 10%), 1.2 % of agar, and 0.18 % of nipagin. We used dry yeast (trademark „Lvivski drizhdzhi") that contained 43 % of proteins and 41 % of carbohydrate. The protein-to-carbohydrate ratio was calculated in accordance with the media composition percentage. The protein-to-carbohydrate ratio of all diets is shown in **Table**. Larvae were grown on the experimental media, and the day after eclosion flies were transferred to the standard medium and held for an additional day for mating. The two-day-old flies were separated by sex and frozen in liquid nitrogen for further biochemical assays.

The composition of the developmental diet and P:C ratio

Dry yeast, %	Sucrose, %	Protein, %	Total carbohydrate, %	P:C ratio
2	10	0.86	10.82	**0.08**
5	10	2.15	12.05	**0.18**
2	1	0.86	1.82	**0.47**
5	1	2.15	3.05	**0.70**
2	0	0.86	0.82	**1.05**
5	0	2.15	2.05	**1.05**

The developmental rate. The development was assessed by counting the number of generated pupae every 6/6/12 h (at 9 am, 3 pm, and 9 pm), starting on the fifth day after egg deposition. The total number of pupae was considered as 100 % and the pupation on each day was expressed as the percentage of pupae formed over this time (Lozinsky *et al.*, 2012).

Determination of wet body mass and dry body mass. For measurement of wet or dry weight, 20 larvae or flies were weighed using RADWAG balance (Radom, Poland) and transferred to a 0.5 mL plastic vial with a cut bottom. The flies were dried at 60 °C with the subsequent weighing after two days.

Hemolymph extraction. Larval hemolymph was extracted by making a small cuticular tear just in front of the caudal spiracles. Anesthetized flies were pierced in the thoracic segment of the body. Next, either larvae or flies were gently transferred into a plastic tube (0.5 mL with a hole on the bottom) and placed in a larger tube (1.5 mL) with further centrifugation (7000 g, 8 min, 21 °C). The collected hemolymph was treated with 0.154 % dithiothreitol. The hemolymph was deproteinized by heat treatment at 70 °C for 5 min followed by centrifugation (16000 g, 15 min, 4 °C) (Rovenko *et al.*, 2015). Supernatants were used to measure circulating glucose.

Body glucose and glycogen assay. Pre-weighed bodies of larvae or flies were homogenized in 50 mM sodium phosphate buffer (SPB) at a 1:10 ratio (fly weight/SPB

volume), centrifuged (13000 g, 15 min, 4 °C), and used for determination of glucose and glycogen levels in the body. Measurements were performed using a glucose assay kit (Liquick Cor-Glucose diagnostic kit, Cormay, Poland, Cat. #2-203). Glycogen was converted into glucose by incubation of supernatants with amyloglucosidase from *Aspergillus niger* (Sigma-Aldrich Chemie GmbH, #10115) for 18 h at 37 °C.

TAG assay. Larvae and imago were weighed and homogenized in phosphate-buffered saline supplemented with Tween 20 (PBST) (pH 7.4, 0.05% Triton X100). Homogenates were incubated in a water bath (95 °C) for 10 min and then centrifuged (16000 g, 15 min, 21 °C). The resulting supernatants were used for TAG assay with the Liquick Cor-TG diagnostic kit (Cormay, Poland).

Total lipid concentration was determined as described previously (Wawrik & Harriman, 2010) using diagnostic kit BIO-TEST TL180 (Erba Lachema s.r.o., Czech Republic). The weighed flies were homogenized in 96% cold (4 °C) ethanol (1:15 w:v) and 75 µl of homogenates were mixed with an equal volume of chloroform and centrifuged (8000 g, 2 min, 21°C). Vials with 40 µL of supernatant were stored on ice until all samples had been evaporated to dryness. Dry samples were incubated in a water bath (95 °C) for 20 min with 200 µL H_2SO_4 (concentrated). Next, 200 µL of kit reagent and 1 mL of concentrated H_2SO_4 were added to the cooled samples for a total volume of 1.4 mL. Absorbance was determined spectrophotometrically at 440 nm.

Statistical analysis. Data are presented as mean ± SEM. To define differences between groups, all data were subjected to analysis of variance (ANOVA) followed by Tukey test. Differences between groups were considered statistically significant when p <0.05. Graphing and statistical analysis were performed using GraphPad Prism.

RESULTS AND DISCUSSION

We have extended previous studies to investigate the effects of macronutrient balance in developmental media on metabolic traits in larvae and *Drosophila* imago flies of both sexes (Klepsatel *et al.*, 2020; Lushchak *et al.*, 2023; Strilbytska *et al.*, 2022). Although it has been proven that developmental diet directly influences lifespan in flies (Klepsatel *et al.*, 2020; Krittika *et al*., 2019), the effect of macronutrient balance on metabolic parameters during the development remains less clear.

In the present study, we used sucrose-free (0%S), low-sucrose (1%S) and high-sucrose (10%S) media with low (2%Y) or high (5%Y) yeast content to generate media with a range of P:C ratio from 0.08 to 1.05. Hence, we were able to track the impact of both macronutrients on development as well as the influence of P:C ratio. Moreover, we tested diets with 1.05 P:C ratio generated either by 2 % of yeast or 5 % of yeast to demonstrate that macronutrient balance, rather than total calorie intake, is the main driver of metabolism and aging processes. We found that the P:C ratio of the diet significantly affected the development of *D. melanogaster*. The pupation rate was slowed down with the decrease in dietary P:C (**Fig. 1*A***). Larvae pupated slower under the consumption of 10%-sucrose-containing media as compared to sucrose-free media. We also observed a lower pupation rate under consumption of the media with 2 % of yeast as compared to 5 % regardless of the sucrose content (**Fig. 1*A***). Similarly, it was previously demonstrated, that larval overnutrition by a high-sucrose diet significantly prolonged pupation time (Klepsatel *et al.*, 2020; Strilbytska *et al.*, 2022) and produced adults with higher levels of whole-body lipids and protein (Musselman *et al.*, 2011). Extended developmental time under a high-sucrose diet may be due to the fact that

the larvae ingested more carbohydrates on high sucrose diet, herewith consuming less food and obtaining less protein derived from yeast (Rovenko *et al.*, 2015).

In the current study, median pupation time depended on the dietary P:C ratio ($F_{5,24}$ = 6.523, P = 0.0006). Median pupation time was about 177 h on 0.08 P:C ratio diet (**Fig. 1*B***). Larvae exposed to 0.18, 0.70 and 1.05 (5Y) P:C diets had ~20 % lower median pupation time as compared to 0.08 P:C ratio diets (p <0.04). Moreover, we observed a 17 % lower median pupation time in larvae fed by 1.05 (5Y) as compared to 1.05 (2Y) (p = 0.0274), suggesting the determining role of dietary yeast in developmental processes.

Juvenile hormone (JH) and 20-hydroxyecdysone (20-HE) are involved in the regulation of developmental processes in insects (Flatt *et al.*, 2005) and are highly dependent on nutritional status (Bond *et al.*, 2010). In response to changes in nutritional conditions, insulin signaling induces secretion of α-ecdysone that, in turn, modulates larval growth (Mirth *et al.*, 2005).

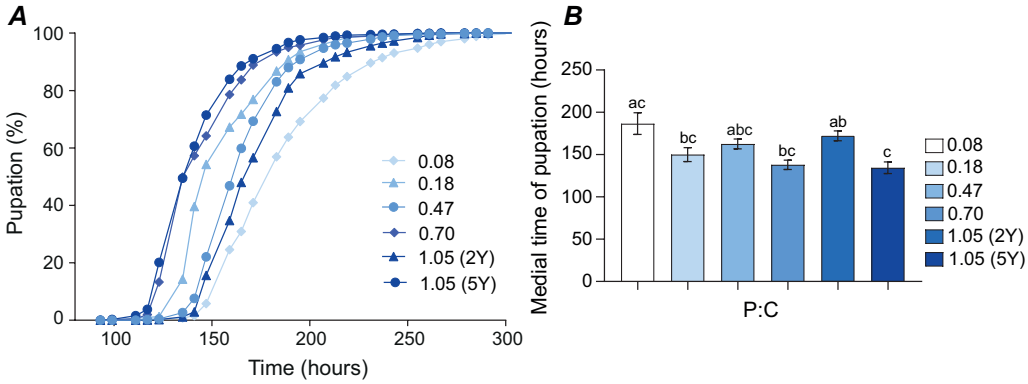

Fig. 1. Dietary protein-to-carbohydrate ratio of 0.08–1.05 affects the pupation rate of flies *Drosophila*. Graphs show the percentage of larvae that pupated over time (***A***) and median pupation time (***B***)

Dietary P:C ratio in larval food affected hemolymph glucose concentration (**Fig. 2*A***; F = 10.08, p < 0.0001). Larvae that developed on a 0.08 and 0.18 P:C diet had about 1.5–2.5-fold higher glucose concentration in hemolymph than those developed on the diets with a higher P:C ratio (**Fig. 2*A***; Tukey test, p <0.05). Dietary P:C ratio had no impact on body glucose content in larvae (**Fig. 2*B***). The amount of glycogen in larvae was dependent on macronutrient balance in the developmental diet (F = 6.615, p = 0.0014). Larvae reared on the diet with 0.08 P:C ratio had 57–70 % lower glycogen content than those reared on the food of 0.47–1.05 P:C (**Fig. 2*C***; Tukey test, p <0.05). Indeed, glycogen level was shown to be lower in larvae fed a high-sugar diet (Musselman *et al.*, 2011). Larvae consumed more food at a low sucrose diet, overeating with yeast (Bruce *et al.*, 2013) which may be the main reason for extended glycogen storage.

Triglyceride levels in larvae depended on macronutrient balance in the developmental diet (F = 4.352, p = 0.0071). As expected, glycogen level was highly dependent not only on macronutrient balance but on total calorie intake. TAG content was significantly increased in larvae reared on medium with P:C ratio 0.47 as compared to 0.18 and 0.7–1.05 (**Fig. 2*D***; Tukey test, p <0.05). The level of total lipid depended significantly on P:C ratio in the developmental diet (F = 7.181, p = 0.0001). We observed

40–45 % higher level of total lipids in larvae reared on the medium with 0.08 P:C ratio as compared to 0.47–1.05 P:C (**Fig. 2*E***; Tukey test, $p < 0.05$). It was recently demonstrated that TAG levels are high in larvae reared on a diet with high sucrose content, but not on high-fat or high protein diets (Musselman *et al.*, 2011). Wet larvae body mass was significantly dependent on dietary P:C ratio ($F = 6.180$, $p = 0.0003$). Larvae fed with food with 0.08 P:C ratio displayed ~50 % lower weight as compared to all other experimental media (**Fig. 2*F***; Tukey test, $p < 0.05$).

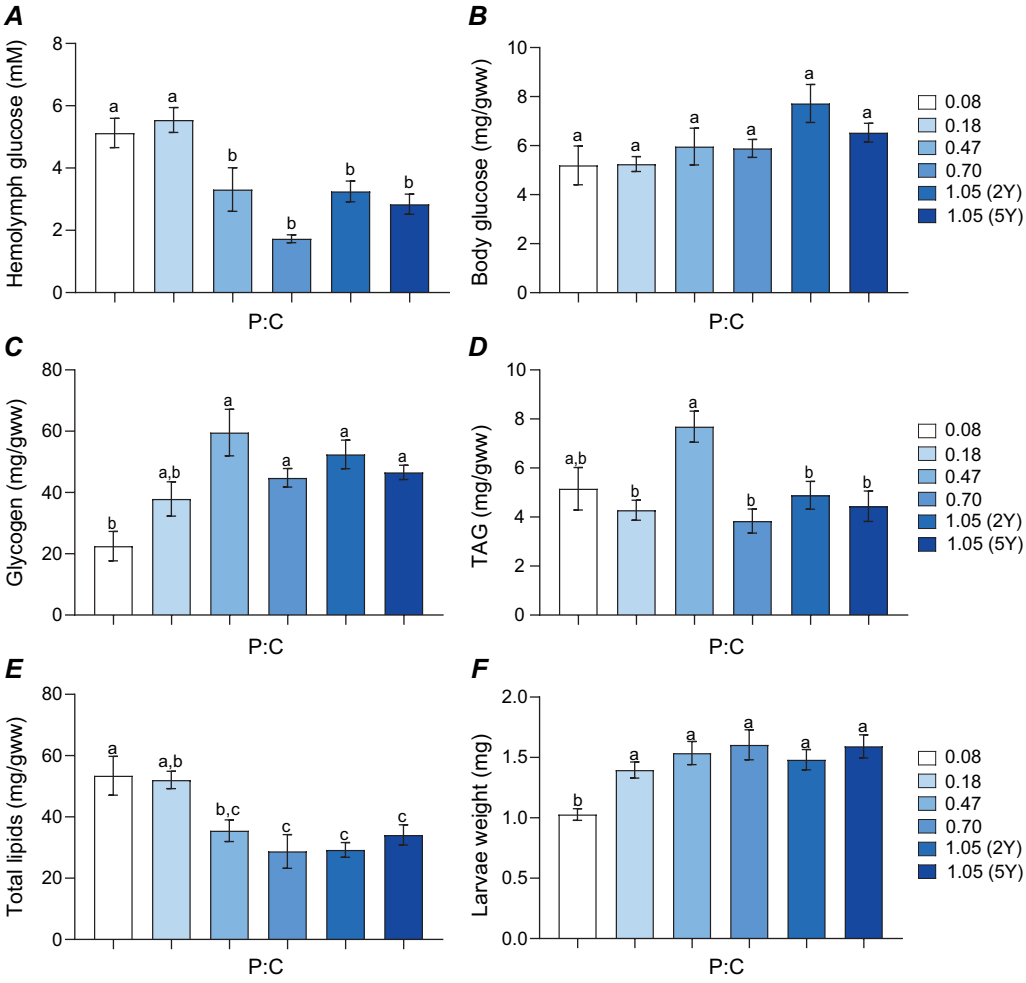

Fig. 2. The levels of hemolymph glucose (***A***), body glucose (***B***), glycogen (***C***), triglycerides (***D***), total lipids (***E***) and body weight (***F***) of *Drosophila* larvae reared on media of different P:C ratio. Results represent the mean ± SEM of 4–7 replicates per group. a, the highest mean among all tested groups; b, significant difference from "a"; c, significant difference from "a" and "b"; ($p < 0.05$). Bars sharing the same letter are not significantly different according to Tukey's test

We also demonstrated that the nutritional conditions experienced during early development have strong effects on adult metabolic traits of *D. melanogaster*. The hemolymph glucose levels in imago males ($F = 7.645$, $p = 0.0004$) and females ($F = 5.867$,

p = 0.0012) depended significantly on P:C ratio in the developmental diet. Higher circulating glucose levels in male flies were found under consumption of the media with 0.08 and 0.18 P:C ratio as compared to 1.05 P:C, regardless of yeast concentration (**Fig. 3*A***; Tukey test, p <0.05). Similarly, female flies, that developed on 0.08 and 0.18 P:C media displayed ~40 % higher hemolymph glucose content as compared to 1.05 P:C on both 2 and 5 % of yeast (**Fig. 3*B***; Tukey test, p < 0.03). It was also previously demonstrated that an imbalanced diet disrupts metabolic homeostasis in adult *D. melanogaster* and promotes insulin-resistant phenotypes (Morris *et al*., 2012).

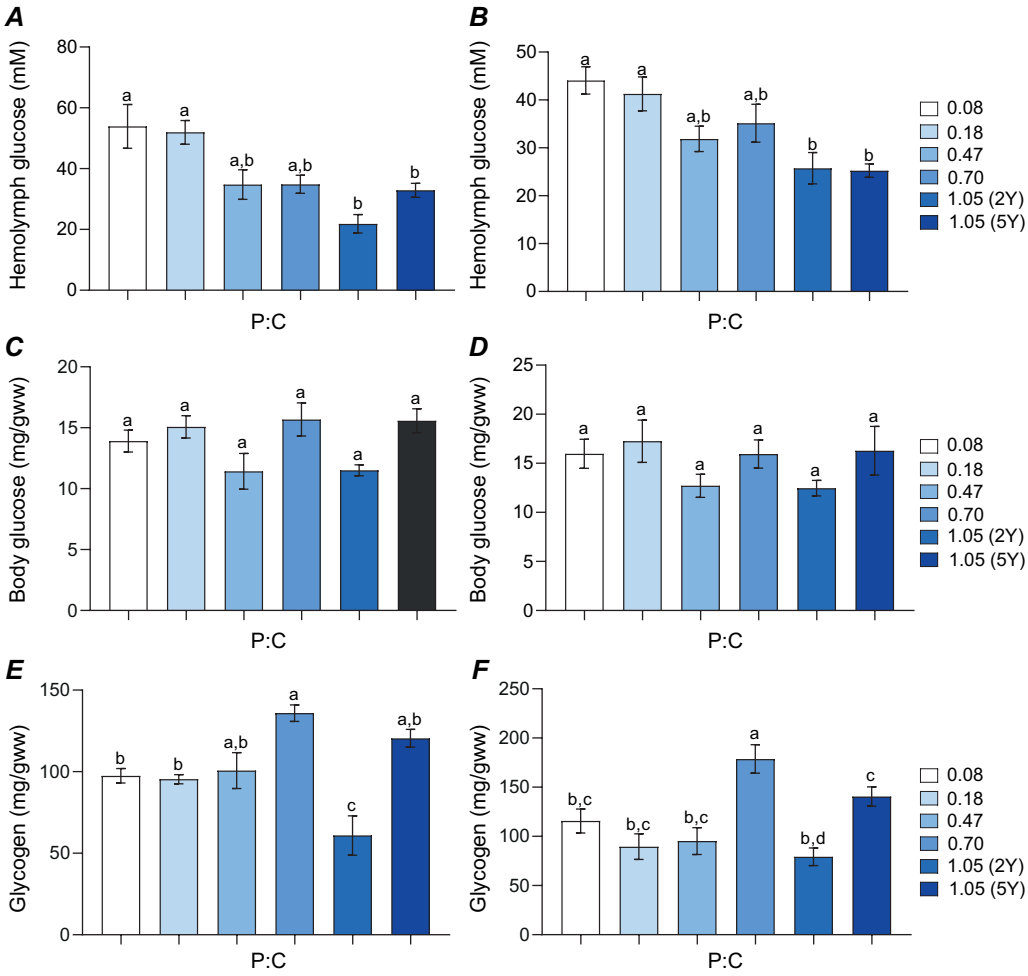

Fig. 3. Levels of hemolymph glucose (***A*** – males; ***B*** – females), body glucose (***C*** – males; ***D*** – females) and glycogen (***E*** – males; ***F*** – females) in adult *Drosophila* that were grown on food with different P:C ratio. Results represent the mean ± SEM of 3–6 replicates per group. a, the highest mean among all tested groups; b, significant difference from "a"; c, significant difference from "a" and "b"; (p <0.05). Bars sharing the same letter are not significantly different according to Tukey's test

The amount of glycogen in flies significantly depended on P:C ratio of the developmental diet (males: F = 11.42, p <0.0001; females: F = 9.707, p <0.0001). Glycogen

levels were reduced in males derived from sucrose-deprived larvae reared on 1.05 P:C media as compared to all sucrose-enriched media (**Fig. 3*E***; Tukey test, p <0.03). A higher glycogen pool was observed in females that were fed during development by 0.7 P:C medium as compared to all other experimental diets (**Fig. 3*F***; Tukey test, p <0.04). Consumption of the medium with P:C of 1.05 composed of 2Y during development led to a lower glycogen pool in flies of both sexes as compared to 1.05 P:C media composed of 5Y (**Fig. 3*E***, ***F***; Tukey test, p <0.05). Body glucose contents in male and female flies were not affected by P:C ratio in the developmental diet (**Fig. 3*C, D***).

We have found significant effects of developmental dietary P:C ratio on the body weight of female flies (F = 8.768, p <0.0001) (**Fig. 4*B***). Females that developed on 0.7–1.05 P:C media had significantly higher body weight as compared to 0.08 P:C medium (**Fig. 4*B***; Tukey test, p <0.02). Body weight of male flies was not affected by larval macronutrient balance (**Fig. 4*A***). Accordingly, it was recently shown that high-sugar diets caused a decrease in water content (Rovenko *et al.*, 2015), which may be the reason for lower larval body weight. Moreover, a high-sugar diet was shown to decrease the size of both larvae and adults due to insulin resistance (Graham & Pick, 2017). Consistent with these previous results, we found that both larvae and adults displayed lower body weight when fed high sucrose diets regardless of yeast content.

The level of TAG in imago depended on P:C ratio in the developmental diet (males: F = 7.806, p = 0.0002; females: F = 3.808, p = 0.0106). Particularly, levels of TAG were significantly higher in male flies originating from larvae fed with a diet with 0.08 P:C than in those fed on media with 0.18-1.05 P:C ratio (**Fig. 4*C***; Tukey test, p <0.05). Moreover, we found higher TAG levels in female flies that developed on 0.08 P:C medium as compared to 0.7–1.05 media (**Fig. 4*D***; Tukey test, p <0.02). The study by Birse and colleagues (2010) showed increased TAG levels in flies fed with a high-fat diet. High-sugar feeding led to increased TAG storage also in adult *Drosophila* (Flatt *et al.*, 2005). Our finding are in good agreement with the previous data claiming that a yeast-poor developmental diet increases fat reserves in adult flies (Flatt *et al.*, 2005).

The amount of total lipids (TL) in flies significantly depended on P:C ratio in the developmental diet (males: F = 10.77, p <0.0001; females: F = 3.089, p = 0.0229). The level of total lipids was increased in two-day-old males who consumed diets with low P:C ratio (0.08 and 0.18) during development as compared to 0.7–1.05 P:C (**Fig. 4*E***; Tukey test, p < 0.05). Also, a 37 % higher level of total lipids was observed in females who fed with 0.18 P:C diet as compared to the ones that developed on 1.05 P:C diet, regardless of yeast concentration (**Fig. 4*F***; Tukey test, p <0.05). Consequently, flies that developed on low P:C media become obese and exhibit severe symptoms of hyperglycemia. Accordingly, it was previously shown that excessive sugar intake in *Drosophila* larvae could enhance levels of lipids and glycogen, increase dry body mass, and decrease water content, i.e. result in an obese phenotype (Rovenko *et al.*, 2015). High-sugar diets contribute to the decreased size of both larvae and adults due to insulin resistance (Graham & Pick, 2017). Moreover, the hyperglycemic effect caused by a high-sugar developmental diet persisted in adult flies of both sexes.

Consequently, a low P:C developmental diet has a considerably more adverse effect on flies than a high P:C diet with respect to all traits tested. Indeed, high-sugar developmental diets induced hyperglycemia and obesity in imago. Similarly, the previous studies in *Drosophila* showed that high-sugar-fed larvae were hyperglycemic and accumulated more fat (Musselman *et al.*, 2011).

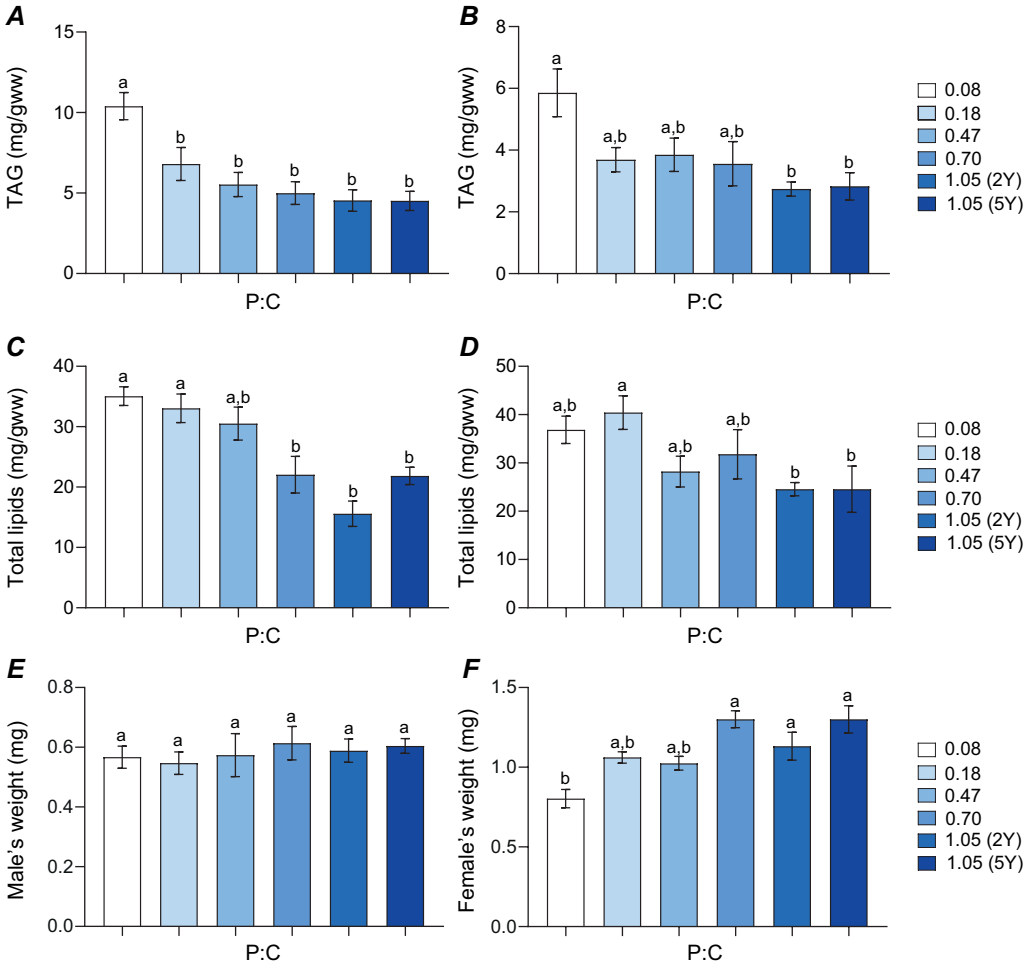

Fig. 4. The level of triglycerides of (***A*** – males; ***B*** – females), total lipids (***C*** – males; ***D*** – females) and dry body weight (***E*** – males; ***F*** – females) in two-day-old flies *D. melanogaster*, reared on food with different P:C ratio. Results represent the mean ± SEM of 4–7 replicates per group. a, the highest mean among all tested groups; b, significant difference from "a"; (p <0.05). Bars sharing the same letter are not significantly different according to Tukey's test

We presume that diet-induced effects on fly metabolic traits represent adaptive responses to the developmental diet. *Drosophila* possess unique metabolic adaptations that include a network comprising intracellular energy sensors, transcriptional regulators, hormonal and neuronal mechanisms (Chng *et al*., 2017). Metabolic homeostasis is maintained by intracellular sensors (Mondo-Mlx, ATP-sensitive K^+ channel, HNF4a), neuronal networks (Gr43a-, diuretic hormone 44, and SCL5A11-expressing neurons) endocrinal signals (occur in the corpora cardiaca) and in the fat body cells (CCHamide-2, Unpaired 2) (Chng *et al*., 2017). These highly conserved mechanisms coordinate animal behavior and metabolism.

Various studies indicated that the risk of many age-related diseases can be determined by factors acting during early development (Vaiserman & Lushchak, 2019).

Unbalanced nutrient intake during the prenatal period can cause dysfunctional pancreatic beta cells thus predisposing the development of type 2 diabetes (T2D) in later life. Mechanisms of epigenetic regulation were shown to play a central role in the developmental programming of T2D (Vaiserman & Lushchak, 2019). In this regard, the role of diet-induced changes in gene regulation through epigenetic factors must be determined.

CONCLUSION

Macronutrients and the balance between dietary components can significantly alter fundamental processes associated with development, physiology and behavior in *D. melanogaster*. The observed effects are more prevalent in larvae but persist into adulthood and were especially clear with respect to development and fly metabolism. While the metabolic profiles of adults are influenced by the developmental rearing diet, the specific mechanisms involved remain unclear. Phenotypic plasticity influenced by food composition during early stages of development may be an important strategy in boosting the beneficial metabolic changes, and sustaining healthy aging.

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COMPLIANCE WITH ETHICAL STANDARDS

Conflict of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHORS CONTRIBUTIONS

Conceptualization, [L.O.]; methodology, [S.O.]; formal analysis, [S.O.; Y.I.].; investigation, [B.N.; S.N.]; data curation, [L.O.]; writing – original draft preparation, [S.N.; S.O.]; writing – review and editing, [L.O.; Z.O.]; visualization, [B.V.].

All authors have read and agreed to the published version of the manuscript.

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ВІДНОШЕННЯ ПРОТЕЇНІВ ДО ВУГЛЕВОДІВ У ХАРЧОВОМУ РАЦІОНІ ВПЛИВАЄ НА МЕТАБОЛІЗМ ЛИЧИНОК ТА ІМАГО *DROSOPHILA*

***Надія Стефанишин*[1], *Ольга Стрільбицька*[1], *Надія Бурдилюк*[1], *Олена Задорожна*[2], *Володимир Бубало*[3], *Ігор Юркевич*[1], *Олег Лущак*[1,4]**

[1] *Прикарпатський національний університет імені Василя Стефаника*
вул. Шевченка, 57, Івано-Франківськ 76000, Україна

[2] *Уманський державний педагогічний університет імені Павла Тичини*
вул. Садова, 2, Умань, Черкаська обл. 20300, Україна

[3] *Лабораторія експериментальної токсикології та мутагенезу,*
Науковий центр превентивної токсикології, харчової та хімічної безпеки
імені академіка Л. І. Медведя, МОЗ України
вул. Героїв Оборони, 6, Київ 03680, Україна

[4] *Університет досліджень та розвитку*
вул. Шота Руставелі, 13А, Івано-Франківськ 76018, Україна

Обґрунтування. Живлення під час росту й розвитку *Drosophila* впливає на різноманітні ознаки не тільки на личинковій стадії, але й на стадії дорослих мух, зокрема, на тривалість життя, розмноження, метаболізм і стійкість до стресових факторів. У цьому дослідженні ми перевірили гіпотезу про те, чи відношення протеїнів до вуглеводів (П : В) у харчовому раціоні під час розвитку мух може бути пов'язане зі змінами метаболізму личинок та імаго *Drosophila*.

Матеріали та методи. У цьому дослідженні використовували лінію *Canton-S Drosophila melanogaster*. Личинки споживали середовище з різним відношенням П : В. Експериментальне середовище містило 2 % або 5 % сухих дріжджів і 0 %, 1 % або 10 % сахарози. Ми визначали швидкість розвитку, вологу або суху масу тіла та рівні метаболітів, включаючи глюкозу, глікоген, триацилгліцериди (ТАГ) і загальні ліпіди. Швидкість розвитку аналізували за допомогою підрахунку кількості залялькованих лялечок кожні 6/6/12 год. Для того, щоб виміряти вологу або суху масу, 20 личинок чи мух зважували і переносили у пластиковий флакон зі зрізаним дном. Мух висушували за 60 °C з подальшим зважуванням через 2 доби. Іншу дводенну когорту мух розділяли за статтю і заморожували в рідкому азоті для подальших біохімічних визначень. Глюкозу в гемолімфі, загальну концентрацію ліпідів, триацилгліцеридів, вміст глюкози та глікогену в тілі визначали спектрофотометрично.

Результати. Ми виявили, що низьке відношення П : В у харчовому раціоні (0,08) сповільнювало заляльковування на ~20 % і призводило до зниження маси тіла. Рівень глюкози у гемолімфі личинок, а також у гемолімфі імаго був обернено пропорційним відношенню П : В у харчовому раціоні. У личинок, які розвивалися на середовищі з низьким відношенням П : В, рівень глікогену був нижчим, однак рівень ліпідів виявився вищим. Відношення П : В у харчовому раціоні під час розвитку *Drosophila* також впливає на метаболічні показники, а саме: вміст глюкози в гемолімфі, вміст глікогену, триацилгліцеридів і загальних ліпідів у самців і самок імаго. Одночасне обмеження сахарози та надмірне споживання протеїну призводило до зниження рівня глюкози й ліпідів у тілі мух *Drosophila*.

Висновки. Наше дослідження дає підстави стверджувати, що умови живлення личинок під час їхнього розвитку призводять до виникнення адаптивних змін, а ці зміни забезпечують такий рівень регуляції, який необхідний, щоб подолати харчовий стрес імаго *Drosophila*.

Ключові слова: розвиток, живлення, макронутрієнти, калорії, плодова мушка *Drosophila*

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