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Lipid accumulation product (LAP): a key indicator for metabolic dysregulation and inflammatory status in obesity

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The Lipid Accumulation Product (LAP) is recognized as an indicator of lipid-induced cellular stress. While its predictive value for conditions like diabetes, liver disease, and metabolic syndrome is established, its specific correlations with individual metabolic and hematological markers within the context of obesity remain less defined. This study sought to comprehensively investigate the links between LAP and a spectrum of metabolic and hematological biomarkers in individuals with obesity. This cross-sectional study involved 304 obese participants. Standard anthropometric measurements [weight, height, waist and hip circumference (WC, HC)] were taken, and dietary intake was assessed via a food frequency questionnaire. Blood samples were analyzed for glucose, insulin, hemoglobin A1C, serum lipids [total cholesterol, triglycerides, low density lipoprotein cholesterol (LDL-C) and high density lipoprotein cholesterol (HDL-C)], and a complete blood cell count. LAP was calculated using WC and triglyceride levels. Participants were categorized into three tertiles based on their LAP values. Individuals in the highest LAP tertile had significantly higher body weight, body mass index, WC, and waist-to-hip ratio than those in the lowest tertile (all $P < 0.05$). Higher LAP tertiles were also associated with increased systolic and diastolic blood pressure, total cholesterol, triglycerides, and reduced HDL-C levels after adjustment for potential confounders. In addition, white blood cell count and mean corpuscular hemoglobin remained significantly higher across LAP tertiles in the fully adjusted models. Supplementary receiver operating characteristic (ROC) analysis demonstrated good discriminatory performance of LAP for identifying metabolic syndrome (AUC = 0.833; 95% CI: 0.779–0.887). Higher LAP was independently associated with an adverse cardiometabolic profile, characterized by greater adiposity, unfavorable lipid parameters, elevated blood pressure, and selected hematological alterations in adults with obesity. These findings support the potential utility of LAP as a simple and accessible marker for identifying individuals at increased cardiometabolic risk. However, prospective studies are needed to determine its predictive value and establish temporal relationships.

Keywords Lipid accumulation product, Obesity, Blood pressure, Serum lipids, Hematological markers, Inflammation, White blood cell count, Cardiometabolic risk

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Obesity has become a global health crisis, with the World Health Organization (WHO) estimating that over 650 million adults worldwide are classified as obese[1]. It is characterized by excessive fat accumulation that significantly increases the risk of numerous chronic diseases, including type 2 diabetes, cardiovascular diseases, and certain types of cancer[2]. The rising prevalence of obesity, particularly in developed countries, has prompted significant concern regarding its long-term impact on public health systems and individual well-being[3]. Obesity is not just a cosmetic issue but a major contributor to metabolic dysfunction. It is associated with a host of altered physiological processes that disturb normal metabolic function, leading to insulin resistance, dyslipidemia, and hypertension. Additionally, obesity often contributes to systemic inflammation, a key factor in the development of various obesity-related diseases. Therefore, understanding the complex mechanisms underlying obesity and its metabolic consequences is essential for developing more effective strategies for prevention and treatment[4].

Lipid Accumulation Product (LAP) is a relatively recent biomarker that has gained attention as an effective indicator of metabolic dysfunction, particularly in obese individuals[5,6]. It is a composite measure based on waist circumference (WC) and triglyceride (TG) levels, which are key components of central obesity and dyslipidemia[6]. Unlike body mass index (BMI), which does not distinguish between different types of body fat or account for the distribution of fat, LAP provides a more direct measure of the lipotoxic effects of abdominal fat[6]. Visceral fat is particularly harmful as it is metabolically active, secreting pro-inflammatory cytokines and contributing to insulin resistance. As a result, LAP has emerged as a valuable tool for assessing metabolic parameters, especially in obese individuals. Metabolic parameters such as insulin resistance, dyslipidemia, and glucose metabolism are central to understanding the pathophysiology of obesity-related diseases like type 2 diabetes (T2DM), cardiovascular diseases (CVDs), and metabolic syndrome (MetS)[7]. Obesity is often associated with a state of chronic low-grade inflammation, driven in part by excess visceral fat. This type of inflammation plays a key role in the development of metabolic disturbances such as insulin resistance and dyslipidemia. While direct inflammatory markers such as cytokines are commonly used to assess this process, hematological parameters, including white blood cell count (WBC) and other components of the complete blood count (CBC), can also serve as indirect markers of systemic inflammation in obese individuals[8,9]. Elevated WBC counts have been linked to increased inflammation and are often observed in individuals with obesity, reflecting the underlying inflammatory burden associated with excess fat[10]. LAP has been found to correlate with inflammatory status in obese individuals[11]; it is not out of expect because LAP combines WC and TG levels, it is likely to reflect both the accumulation of visceral fat and the associated inflammatory processes that contribute to metabolic dysfunction[12]. Moreover, there is a close association between obesity, liver function and LAP[13] and LAP has been suggested as a potent prognostic index for prediction of non-alcoholic fatty liver disease (NAFLD)[13–15] and metabolic dysfunction-associated fatty liver disease[16].

The rising global prevalence of obesity and its associated metabolic and inflammatory complications highlight the urgent need for effective diagnostic tools that can identify individuals at risk for developing obesity-related diseases. Although traditional measures of obesity or dyslipidemia provide some insight into an individual's weight status, they do not fully capture the complexity of metabolic disturbances and inflammation, particularly in obese individuals. LAP has emerged as a promising biomarker that integrates both visceral adiposity and lipid abnormalities, offering a more accurate reflection of metabolic dysfunction in this population. Moreover, although LAP has been proposed as a practical surrogate marker of visceral adiposity and cardiometabolic risk, most previous studies have primarily focused on its association with individual outcomes such as MetS[6,17], diabetes[5], or CVDs[18]. In the study by Kwon S et al.[18], LAP was recognized as an independent marker of visceral adiposity. Similar finding was reported in the study by Yu SR et al.[6] in which LAP was a potent indicator of different obesity phenotypes in Korean adults. Similar findings were reported for the association between LAP and MetS in the study by Raposo MA et al.[17] and the study by Chiang JK et al.[19]. LAP was better than BMI in prediction of CVDs in the study by Kahn HS et al.[20]. A comprehensive assessment of these interrelated domains may provide a more complete understanding of the clinical relevance of LAP in obesity. While, evidence regarding the relationship between LAP and a comprehensive range of anthropometric characteristics, dietary intake, lipid and glycemic biomarkers, liver enzymes, and hematological parameters in adults with obesity remains limited. A more integrated evaluation of these associations may improve our understanding of the clinical relevance of LAP and its potential application as a simple marker for cardiometabolic risk assessment. Therefore, the current cross-sectional study was aimed to evaluate the association between LAP and blood pressure (e.g. systolic blood pressure [SBP] and diastolic blood pressure [DBP]), serum lipids (e.g. low density lipoprotein cholesterol [LDL-C], high density lipoprotein cholesterol [HDL-C], TG, total cholesterol [TC]) glycemic biomarkers (e.g. fasting blood sugar [FBS], hemoglobin A1C [Hb A1C], insulin), hematological profile (e.g. CBC) and liver function tests (alanine aminotransferase [ALT], aspartate aminotransferase [AST], alkaline phosphatase [ALP], albumin, creatinine] among adults with obesity.

Methods and materials

Patients

Participants were recruited from obesity and nutrition outpatient clinics affiliated with Mansoura University, Mansoura, Egypt. Eligible participants were adults aged 25–50 years with obesity, defined as a BMI ≥ 30 kg/m^2. Individuals were excluded if they had a previous diagnosis of T2DM, CVDs, active malignancy, chronic inflammatory or autoimmune disorders, acute or chronic infectious diseases, severe hepatic or renal disease, or had undergone bariatric surgery within the preceding three years. Pregnant or lactating women were also excluded. In addition, individuals receiving lipid-lowering medications or other medications known to substantially affect lipid metabolism or hematological parameters were not eligible for participation. Potential participants were identified through outpatient clinics and invited to attend an initial screening visit, during which eligibility criteria were assessed using medical history, a structured questionnaire, medication history, and

available clinical records. Eligible individuals received detailed information regarding the study objectives and procedures before providing written informed consent.

Following confirmation of eligibility, all participants provided written informed consent prior to enrollment. The study protocol was reviewed and approved by the Deanship of Research and Graduate Studies, Mansoura, Egypt (Ethical approval No. R.26.05.3727). All study procedures were conducted in accordance with the ethical principles of the Declaration of Helsinki and its subsequent amendments. The sample size of 304 participants was calculated using G*Power software to ensure sufficient statistical power to detect meaningful associations with a 95% confidence level, an expected effect size of 0.3, and a power of 80% ($\beta = 0.2$). The calculation also accounted for a potential dropout rate of 10%[21].

Dietary and physical activity assessments

Dietary intake was assessed using a semi-quantitative food frequency questionnaire (FFQ) adapted from a previously developed and validated FFQ that has been widely used in Arab populations, including the Mutaba'ah Study[22]. The final questionnaire included 146 food items covering major food groups, including cereals, dairy products, vegetables, fruits, legumes, meat, fish, eggs, fats and oils, mixed dishes, beverages, sweets, nuts, and seeds. Participants reported their usual dietary intake over the previous year by indicating the frequency and portion size of each food item. Reported intakes were converted into average daily consumption (g/day) using standard household measures. Dietary data were collected in Arabic by trained nutritionists through interviewer-administered interviews and analyzed using Nutritionist IV software (First Databank, San Bruno, CA, USA) to estimate daily energy, macronutrient, and food group intakes. Physical activity (PA) was assessed using the International Physical Activity Questionnaire (IPAQ). Total physical activity was expressed as metabolic equivalent task (MET)-minute/week by summing the MET-minutes derived from walking, moderate-intensity, and vigorous-intensity activities according to the IPAQ scoring protocol. Participants were subsequently classified into low, moderate, or high physical activity levels based on the standard IPAQ classification criteria[23].

Anthropometric assessments and blood pressure

Weight was measured using a calibrated digital scale, with the participant standing barefoot and wearing minimal clothing. Height was measured with a stadiometer or wall-mounted measuring tape, with the participant standing straight against the wall, without shoes, and the head aligned in the Frankfort plane. WC was measured at the narrowest point of the torso or at the midpoint between the lower ribs and the iliac crest with a flexible measuring tape. Hip circumference (HC) was taken at the widest point of the hips and buttocks. The ratio was determined by dividing WC by hip circumference. Waist to hip ratio (WHR) was calculated by measuring both WC and HC. Fat mass (FM) and fat free mass (FFM) were estimated using bioelectrical impedance analysis (BIA). Blood pressure (SBP, DBP) was measured using Omron BP Monitor. Hematologic parameters were analyzed using a coulter count (Coulter International Corporation, Miami, FL, USA).

Laboratory assessments

Following an overnight fast of 10–12 h, venous blood samples were collected from all participants between 8:00 and 10:00 a.m. Serum was separated by centrifugation and immediately analyzed or stored at − 80°C until biochemical analyses were performed. Serum lipid profile, including TC, TG, HDL-C, and LDL-C, FBS, ALT, AST, ALP, albumin, and creatinine concentrations were measured using standardized enzymatic colorimetric methods on a Roche Cobas c501 automated chemistry analyzer (Roche Diagnostics, Mannheim, Germany) according to the manufacturer's instructions. HbA1C was determined using an immunoturbidimetric assay on the same analyzer. Serum insulin concentrations were measured using an electrochemiluminescence immunoassay (ECLIA) with the Roche Elecsys® Insulin assay (Roche Diagnostics, Mannheim, Germany). Hematological parameters, including WBC count, red blood cell (RBC) count, platelet (PLT) count, hemoglobin (Hb), hematocrit (HCT), mean corpuscular volume (MCV), mean corpuscular hemoglobin (MCH), and mean corpuscular hemoglobin concentration (MCHC), were determined from EDTA-anticoagulated whole blood samples using an automated hematology analyzer (Sysmex XN-1000; Sysmex Corporation, Kobe, Japan) following the manufacturer's recommended procedures and routine internal quality control protocols. The LAP was calculated using the sex-specific equations originally proposed by Kahn HS. et al.[24]: LAP = WC [cm] − 65) × TG concentration (mmol/L) for men and LAP = (WC [cm] − 58) × TG concentration (mmol/L) for women. These equations were developed as sex-specific indicators of lipid over accumulation and have been widely used as surrogate markers of visceral adiposity and cardiometabolic risk[5,6]. MetS was defined according to the National Cholesterol Education Program Adult Treatment Panel III (NCEP ATP III) criteria as the presence of three or more of the following components: (1) WC > 102 cm in men or > 88 cm in women; (2) serum TG ≥ 150 mg/dL (1.7 mmol/L) or current treatment for elevated TG; (3) HDL-C < 40 mg/dL in men or < 50 mg/dL in women or treatment for reduced HDL-C; (4) blood pressure ≥ 130/85 mmHg or current antihypertensive treatment; and (5) FBS ≥ 100 mg/dL or treatment for diabetes mellitus[25].

Statistical analysis

Statistical analyses were performed using IBM SPSS Statistics software (version 23; IBM Corp., Armonk, NY, USA). Continuous variables are presented as mean ± standard deviation (SD), whereas categorical variables are expressed as frequencies and percentages. Participants were categorized into tertiles according to their LAP values. Baseline demographic, anthropometric, dietary, biochemical, and hematological characteristics were compared across LAP tertiles using one-way analysis of variance (ANOVA) for continuous variables and the chi-square test for categorical variables. To account for potential confounding, general linear models (GLMs) were additionally performed to compare study variables across LAP tertiles after adjustment for relevant covariates. Dietary variables were adjusted for total energy intake. Anthropometric variables were adjusted for age, sex,

physical activity, smoking education, marital status, and total energy intake. Biochemical and hematological variables were evaluated using two adjusted models: Model 1 included adjustment for age, sex, and total energy intake, whereas Model 2 was additionally adjusted for physical activity, smoking, education, and marital status. Covariates included in the adjusted models were selected a priori based on their biological plausibility and established associations with adiposity and cardiometabolic outcomes reported in previous studies, rather than by automated statistical selection procedures. Regression coefficients (β) and 95% confidence intervals (95% CIs) were reported for the fully adjusted models. Prior to model fitting, multicollinearity among independent variables was assessed using variance inflation factors (VIFs) and tolerance statistics. As a supplementary analysis performed, receiver operating characteristic (ROC) curve analysis was conducted to evaluate the discriminatory performance of LAP for identifying metabolic syndrome. The area under the ROC curve (AUC) and its 95% CI were calculated. The optimal cutoff value was determined using the maximum Youden index (sensitivity + specificity − 1), and the corresponding sensitivity and specificity were reported. All statistical tests were two-sided, and a *P* value < 0.05 was considered statistically significant.

Results

A total of 304 participants were included in the present study and categorized into tertiles according to their LAP values (Table 1). Participants in the higher LAP tertiles were significantly older than those in the lowest tertile (P = 0.006). Although no significant differences were observed in sex distribution, physical activity level, smoking status, educational level, or marital status across LAP tertiles, participants in the highest LAP tertile had significantly greater body weight, BMI, WC, and WHR compared with those in the lower tertiles. These associations remained significant after adjustment for age, sex, physical activity, smoking, education, marital status, and total energy intake (all adjusted P < 0.05). Fat mass percentage differed significantly across tertiles in the crude analysis (P = 0.002); however, this association was no longer significant after multivariable adjustment (P = 0.123). Similarly, no significant differences were observed for height or FFM in either crude or adjusted analyses. No significant differences were observed in total energy intake or the percentage of energy derived from protein, carbohydrate, and fat across LAP tertiles (Table 2). Likewise, intakes of grains, beans, nuts, vegetables, fruits, and red meat did not differ significantly among tertiles in either crude or energy-adjusted analyses. In contrast, dairy intake increased significantly across increasing LAP tertiles and remained significantly associated with LAP after adjustment for total energy intake (P = 0.009).

As shown in Table 3, SBP, DBP, TC, TG, HDL-C, and LDL-C differed significantly across LAP tertiles in the crude analyses. After adjustment for age, sex, and total energy intake, significant differences remained for SBP, DBP, TC, TG, HDL-C, and LDL-C, whereas the association with FBS was attenuated and no longer statistically significant. In the fully adjusted model, which additionally included physical activity, smoking, education, and marital status, significant positive associations were observed between LAP and SBP (β = 0.138, 95% CI: 0.074–0.452, P = 0.013) and TG (β = 0.909, 95% CI: 0.451–0.525, P < 0.001), whereas HDL-C was inversely associated with LAP (β = − 0.048, 95% CI: − 0.388 to 0.053). ALT also showed a statistically significant association with LAP in the fully adjusted model (P = 0.049), while no significant associations were identified for FBS, LDL-C, insulin, HbA1C, AST, ALP, albumin, or creatinine after full adjustment. With respect to hematological parameters (Table 4), WBC count and mean MCH differed significantly across LAP tertiles in both crude and adjusted analyses. These associations remained statistically significant in the fully adjusted model (WBC: β = 0.042, P = 0.048; MCH: β = 0.085, P = 0.043). No significant associations were observed between LAP tertiles and PLT,

Variable	1st tertile (n = 101)	2nd tertile (n = 102)	3rd tertile (n = 101)	P-value *	P-value **
Age (years)	37.34 ± 8.66	40.87 ± 10.46	41.31 ± 9.64	**0.006**	-
Sex (male, n [%])	35 (34.7)	42 (41.2)	46 (45.6)	0.282	-
Physical activity [low, n (%)]	11 (45.8)	14 (46.7)	10 (50)	0.789	-
Smoking [smokers, n (%)]	7 (6.9)	10 (9.8)	16 (15.8)	0.614	-
Education [illiterate, n (%)]	18 (26.9)	11 (19)	18 (36.7)	0.374	-
Marital status [married, n (%)]	38 (37.62)	48 (47.05)	36 (35.64)	0.425	-
Weight (kg)	88.79 ± 13.96	93.88 ± 12.49	95.46 ± 15.27	**0.002**	**0.025**
Height (cm)	162.91 ± 10.29	165.52 ± 10.74	163.33 ± 18.96	0.357	0.208
BMI (kg/m^2)	33.55 ± 4.03	34.61 ± 4.59	35.37 ± 5.14	**0.019**	**0.038**
WC (cm)	101.92 ± 8.92	108.93 ± 8.12	111.44 ± 9.87	**< 0.001**	**< 0.001**
WHR	0.89 ± 0.09	0.92 ± 0.09	0.93 ± 0.09	**0.004**	**< 0.001**
FM (%)	34.52 ± 8.33	36.92 ± 10.20	39.84 ± 10.75	**0.002**	0.123
FFM (%)	55.25 ± 11.96	58.16 ± 11.79	58.20 ± 11.47	0.157	0.091

Table 1. The comparison of general demographic and anthropometric variables across LAP tertiles. LAP, lipid accumulation product; MET, metabolic equivalent; SD, standard deviation; BMI, body mass index; WC, waist circumference; WHR, waist-to-hip ratio; FM, fat mass; FFM, fat-free mass. Values are presented as mean ± SD, except for sex, which is presented as number (%). * Comparisons among LAP tertiles were performed using one-way analysis of variance (ANOVA). **Adjusted P values were obtained using the general linear model after adjustment for age, sex, physical activity, smoking, education, marital status and total energy intake. Bolded values are statistically significant as < 0.05.

Variable	1st tertile (n = 101)	2nd tertile (n = 102)	3rd tertile (n = 101)	P-value*	P-value**
Energy (kcal/day)	2869.62 ± 941.19	2846.29 ± 1003.99	3049.57 ± 1073.96	0.292	–
Protein (% of energy)	12.70 ± 2.22	13.20 ± 2.45	13.42 ± 2.64	0.103	–
Carbohydrate (% of energy)	55.32 ± 9.00	56.95 ± 8.61	56.61 ± 9.55	0.403	–
Fat (% of energy)	31.78 ± 7.55	30.42 ± 6.77	30.10 ± 6.92	0.201	–
Grains (g/day)	497.35 ± 208.13	510.73 ± 254.35	539.98 ± 262.50	0.444	0.777
Beans (g/day)	60.92 ± 67.51	57.73 ± 66.30	58.50 ± 53.67	0.931	0.549
Nuts (g/day)	13.40 ± 15.94	15.81 ± 23.40	17.92 ± 40.22	0.527	0.688
Vegetables (g/day)	333.85 ± 189.95	407.47 ± 422.37	428.87 ± 237.46	0.065	0.081
Dairy (g/day)	322.76 ± 214.49	331.17 ± 243.57	428.88 ± 265.20	**0.003**	**0.009**
Fruits (g/day)	518.10 ± 425.52	509.67 ± 383.41	592.81 ± 503.99	0.336	0.766
Red meat (g/day)	23.68 ± 30.98	24.39 ± 28.82	20.26 ± 16.93	0.312	0.321

Table 2. Comparison of dietary energy, macronutrient, and food group intakes across LAP tertiles. LAP, lipid accumulation product; SD, standard deviation. Values are presented as mean ± SD. *P-values were obtained using one-way analysis of variance (ANOVA). **P-values were obtained using a general linear model (GLM) after adjustment for total energy intake. Bolded values are statistically significant as < 0.05.

Variable	1st tertile (n = 101)	2nd tertile (n = 102)	3rd tertile (n = 101)	β	Lower CI	Upper CI	P-value*	P-value**	P-value***
SBP (mmHg)	113.52 ± 15.15	119.91 ± 14.87	123.63 ± 19.63	0.138	0.074	0.452	**0.001**	**0.006**	**0.013**
DBP (mmHg)	75.44 ± 10.21	79.21 ± 11.52	80.40 ± 14.47	0.025	-0.208	0.346	**0.032**	**0.015**	**0.044**
FBS (mg/dL)	94.23 ± 14.93	96.90 ± 23.99	103.07 ± 29.89	0.007	-0.092	0.073	**0.028**	0.094	0.118
TC (mg/dL)	169.85 ± 33.44	186.80 ± 35.99	202.66 ± 38.23	0.011	-0.071	0.052	**< 0.001**	**< 0.001**	**0.005**
TG (mg/dL)	80.10 ± 22.92	120.85 ± 23.83	222.12 ± 106.31	0.909	0.451	0.525	**< 0.001**	**< 0.001**	**< 0.001**
HDL-C (mg/dL)	46.95 ± 12.13	41.71 ± 9.62	37.52 ± 9.25	-0.048	-0.388	0.053	**< 0.001**	**< 0.001**	**< 0.001**
LDL-C (mg/dL)	106.05 ± 33.53	120.64 ± 34.09	125.66 ± 37.65	0.146	0.044	0.329	**< 0.001**	**0.048**	0.112
Insulin (mIU/L)	15.38 ± 11.00	15.83 ± 9.34	17.11 ± 11.43	0.031	-0.103	0.321	0.549	0.946	0.952
HbA1c (%)	5.64 ± 0.81	5.67 ± 0.90	5.59 ± 0.96	0.028	-1.288	3.444	0.800	0.945	0.792
ALT (U/L)	37.72 ± 76.44	47.22 ± 70.38	32.44 ± 46.96	-0.037	-0.095	0.045	0.272	0.553	**0.049**
AST (U/L)	46.42 ± 71.19	47.41 ± 68.28	30.29 ± 29.06	0.013	-0.070	0.088	0.076	0.060	0.445
ALP (U/L)	390.32 ± 341.40	455.03 ± 394.27	417.70 ± 432.00	0.033	-0.004	0.011	0.510	0.338	0.089
Albumin (g/dL)	3.82 ± 0.92	3.56 ± 0.78	3.48 ± 0.81	-0.032	-3.957	1.246	**0.030**	0.493	0.481
Creatinine (mg/dL)	4.44 ± 4.12	5.05 ± 9.82	4.52 ± 3.99	-0.004	-0.276	0.242	0.812	0.600	0.599

Table 3. Comparison of blood pressure, lipid profile, glycemic markers, and liver enzymes across LAP tertiles. LAP, lipid accumulation product; SD, standard deviation; CI, confidence interval; SBP, systolic blood pressure; DBP, diastolic blood pressure; FBS, fasting blood sugar; TC, Total cholesterol; TG. Triglyceride; HDL-C, high-density lipoprotein cholesterol; LDL-C, low-density lipoprotein cholesterol; HbA1c, glycated hemoglobin; ALT, alanine aminotransferase; AST, aspartate aminotransferase; ALP, alkaline phosphatase. Values are presented as mean ± SD. *P-values were obtained using one-way analysis of variance (ANOVA). **P-values were obtained using a general linear model (GLM) after adjustment for age, sex, and total energy intake; *** Adjusted for age, sex, physical activity, smoking, education, marital status and total energy intake. Bolded values are statistically significant as < 0.05.

RBC, HCT, hemoglobin, MCHC, or MCV after adjustment for potential confounders. To evaluate potential multicollinearity among variables included in the multivariable analyses, collinearity diagnostics were performed (Supplementary Table S1). All tolerance values exceeded 0.20 and all VIF values were below 5, indicating the absence of problematic multicollinearity among the independent variables included in the regression models. As an additional supplementary analysis, ROC curve analysis was performed to evaluate the discriminatory performance of LAP for identifying metabolic syndrome (Supplementary Figure S1 and Supplementary Table S2). LAP demonstrated good discriminatory ability, with an area under the curve (AUC) of 0.833 (95% CI: 0.779–0.887, P < 0.001). The optimal cutoff value determined using the maximum Youden index was 49.23, corresponding to a sensitivity of 87.7% and a specificity of 55.5%, indicating good overall discrimination with high sensitivity for identifying individuals with metabolic syndrome.

Discussion

In the present study, individuals in the highest LAP tertile exhibited greater general and central adiposity, higher blood pressure, a more adverse lipid profile, and elevated white blood cell counts compared with those in the lowest tertile (Fig. 1). While previous studies have primarily examined the association of LAP with individual

Variable	1st tertile (n = 101)	2nd tertile (n = 102)	3rd tertile (n = 101)	β	Lower CI	Upper CI	P-value*	P-value**	P-value***
PLT ($\times 10^9$/L)	206.29 ± 75.78	221.48 ± 117.88	219.65 ± 105.07	0.008	-0.056	0.063	0.516	0.634	0.760
WBC ($\times 10^9$/L)	7.73 ± 3.54	9.05 ± 4.49	8.20 ± 3.02	0.042	-1.072	2.093	**0.031**	**0.040**	**0.048**
RBC ($\times 10^{12}$/L)	3.91 ± 0.73	3.93 ± 0.75	4.14 ± 2.73	0.135	0.129	6.769	0.566	0.665	0.542
HCT (%)	34.11 ± 8.07	33.10 ± 5.67	33.79 ± 7.64	-0.065	-1.253	0.431	0.617	0.799	0.801
Hemoglobin (g/dL)	11.20 ± 2.06	11.83 ± 6.60	12.31 ± 9.32	-0.012	-0.916	0.758	0.505	0.623	0.551
MCHC (g/dL)	33.61 ± 2.19	33.65 ± 1.94	33.57 ± 2.64	0.015	-2.402	3.019	0.977	0.936	0.929
MCH (pg)	28.59 ± 3.95	29.70 ± 2.35	29.37 ± 2.57	0.085	-0.627	3.128	**0.032**	**0.027**	**0.043**
MCV (fL)	91.28 ± 74.45	83.90 ± 10.26	84.90 ± 8.29	-0.054	-0.180	0.072	0.442	0.437	0.437

Table 4. Comparison of hematological parameters across LAP tertiles. LAP, lipid accumulation product; SD, standard deviation; CI, confidence interval; PLT, platelet; WBC, white blood cell; RBC, red blood cell; HCT, hematocrit; MCHC, mean corpuscular hemoglobin concentration; MCH, mean corpuscular hemoglobin; MCV, mean corpuscular volume. Values are presented as mean ± SD. *P-values were obtained using one-way analysis of variance (ANOVA). **P-values were obtained using a general linear model (GLM) after adjustment for age, sex, and total energy intake. *** Adjusted for age, sex, physical activity, smoking, education, marital status and total energy intake. Bolded values are statistically significant as < 0.05.

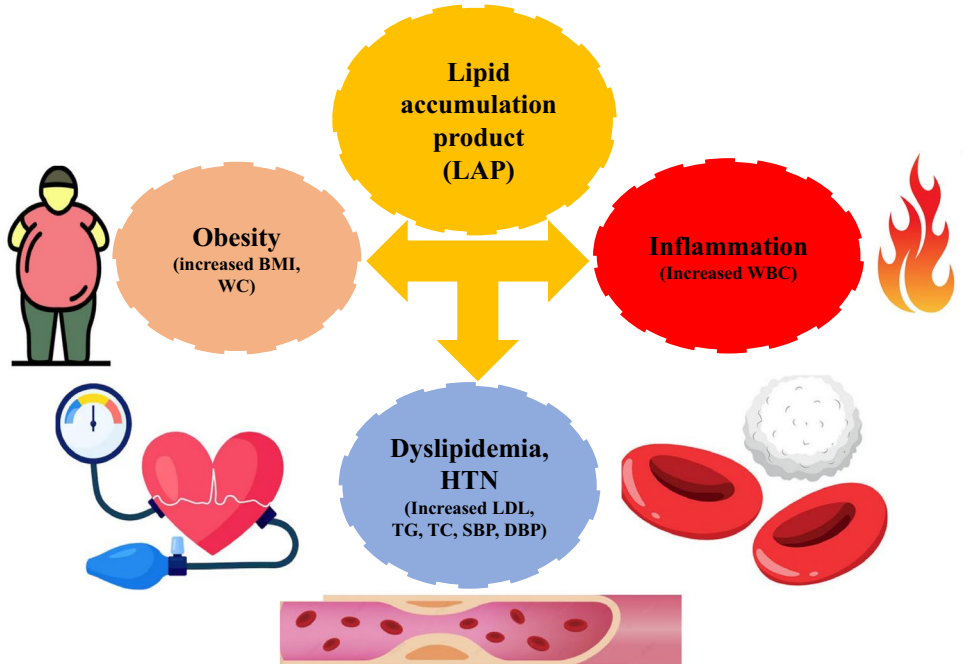

Fig. 1. .

cardiometabolic outcomes, the present study provides a comprehensive evaluation of its relationship with anthropometric characteristics, metabolic biomarkers, liver enzymes, and hematological parameters in adults with obesity, thereby offering a broader understanding of the clinical relevance of LAP. Same as our results, Kwon S et al.[18], the highest quartile of LAP was associated with abdominal obesity risk independent from confounders.

Kahn HS et al.[20] suggested in their study that LAP acts better than BMI for recognition of cardiovascular disease risk in a population-based comparison of national health and nutrition examination survey (NHANES). LAP index was first defined by Kahn as a lipid over accumulation[20], it is an easy and inexpensive marker that can be used in clinical evaluation, the association of LAP with blood pressure and hematological parameters is a novel, under-researched issue. We observed a higher blood pressure in higher LAP tertiles; although there is no study that evaluate direct association of LAP with blood pressure, however, several studies have identified LAP as a potent predictor of MetS that included blood pressure as one of its main integrates; in the study by Chiang JK et al.[19], LAP was introduced as the best predictor of MetS compared with other adiposity markers among Taiwanese people aged 50 years and over. In another cross-sectional study, the ROC curves analyzes of LAP, demonstrated the best diagnostic accuracy for prediction of metabolic syndrome according to the international diabetic federation criteria[17].

Obesity is recognized as a chronic inflammatory situation, and elevated white blood cell counts (WBC) have widely recognized as marker of inflammatory status among obese individuals[9,26,27]. Similar studies reported a

positive association between WBC, serum triglyceride and atherogenic index of plasma (AIP) among obese women[28]. In the same study, hemoglobin and hematocrit were in consistent relationship with LDL- C. Another study reported the correlation between hypertriglyceridemia and higher white blood cell count in a population-based study[29]. There are some other studies that reported the positive association between WBC and serum triglyceride[30–32]. It is suggested that TG -rich lipoproteins (TRLs) interact with leukocytes and activate the leukocytes; this triglyceride-mediated activation of leukocyte is an alternative pro-inflammatory and pro-atherogenic mechanism of hypertriglyceridemia[33].

In our study, among dietary intake of nutrients and food groups, higher dairy products intake was observed in higher LAP tertiles. This dairy product was a combination of low-fat and high-fat dairies and the atherogenic potential of high-fat dairy products is established before[34,35].

An additional finding of the present study was the independent association of higher LAP with increased WBC count and MCH after adjustment for potential confounders. The observed association with WBC is biologically plausible, as LAP reflects visceral fat accumulation, which is recognized as a metabolically active tissue capable of promoting chronic low-grade systemic inflammation[5,18,24]. Excess visceral adiposity is characterized by adipocyte hypertrophy, macrophage infiltration, and increased secretion of pro-inflammatory cytokines, including tumor necrosis factor-α (TNF-α) and interleukin-6 (IL-6)[2,4,11]. These inflammatory mediators stimulate leukocyte production and activation, contributing to elevated circulating WBC counts[36,37]. Furthermore, increased free fatty acid flux from visceral adipose tissue may induce lipotoxicity and oxidative stress, thereby amplifying inflammatory signaling and immune cell recruitment[38,39]. Although the underlying mechanisms linking LAP with MCH are less well established, alterations in erythrocyte indices may reflect metabolic and inflammatory disturbances accompanying obesity. Nevertheless, the association between LAP and MCH should be interpreted cautiously and warrants confirmation in future mechanistic and longitudinal studies.

The present findings are generally consistent with previous investigations demonstrating that higher LAP is closely associated with an unfavorable cardiometabolic profile. Earlier studies have consistently reported significant associations between elevated LAP and MetS, insulin resistance, T2DM, NAFLD, and cardiovascular risk, highlighting its value as a surrogate marker of visceral adiposity and metabolic dysfunction[5,6,15,17,19,24]. Our findings extend these observations by showing that individuals with higher LAP not only exhibited adverse anthropometric and metabolic characteristics but also had higher blood pressure and alterations in selected hematological parameters, particularly white blood cell count and mean corpuscular hemoglobin. Evaluating these diverse clinical and biochemical characteristics simultaneously within the same cohort provides a broader perspective on the potential clinical relevance of LAP in adults with obesity.

The present study has several strengths. To our knowledge, this is among the first studies to comprehensively examine the associations between the LAP and a broad range of anthropometric, dietary, metabolic, hepatic, and hematological parameters within the same study population. The use of standardized protocols for data collection, validated dietary assessment methods, and comprehensive adjustment for major demographic and lifestyle-related confounders, including age, sex, total energy intake, physical activity, smoking status, educational level, and marital status, further strengthens the validity of our findings.

Nevertheless, several limitations should be acknowledged. First, the cross-sectional design precludes any inference regarding temporal or causal relationships between LAP and the investigated outcomes. Second, although multiple potential confounders were considered, residual confounding cannot be completely excluded. Finally, information regarding alcohol consumption was not systematically collected and therefore could not be incorporated into the adjusted analyses. Prospective longitudinal studies are warranted to confirm these findings and clarify the temporal relationships between LAP and cardiometabolic health.

Conclusion

In conclusion, higher LAP values were associated with a less favorable cardiometabolic profile, characterized by greater adiposity, higher blood pressure, adverse lipid parameters, and selected hematological alterations in adults with obesity. These associations remained significant after adjustment for major demographic and lifestyle-related confounders, supporting the robustness of the observed findings. Furthermore, the supplementary ROC analysis demonstrated that LAP showed good discriminatory ability for identifying individuals with MetS, suggesting its potential clinical utility as a simple and inexpensive marker for cardiometabolic risk stratification. Given its simplicity, low cost, and reliance on routinely available clinical measurements, LAP may represent a practical tool for identifying individuals with obesity who are at increased cardiometabolic risk and may benefit from closer metabolic evaluation. However, prospective longitudinal studies are warranted to confirm its predictive performance, establish its role in routine clinical risk stratification and to determine whether LAP can predict the development of metabolic disorders and related clinical outcomes over time.

Data availability

The datasets of the current study are available from the corresponding author on reasonable request.

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Author contributions

AAMAES, writing the first draft of the paper, data analysis, hypothesis generation and data acquisition; KEAA, data collection, data analysis, hypothesis generation and revision of paper; He also supervised the project with RA. RB was involved in manuscript writing and hypothesis generation and data conceptualization. SA, IMA and MAA were involved in data collection, nutritional data analysis and FFQ analysis and data entry, writing the related part of the manuscript, MSM and SAA were also involved in data collection, writing the manuscript, subjects' recruitment; AAF was involved in data collection, writing the manuscript, subjects' recruitment; IK was involved in data analysis, statistical approaches, writing the related parts of the manuscript. All authors read and approved the final version of article for submission.

Declarations

Competing interests

The authors declare no competing interests.

Ethics approval and consent to participate

The funding and ethical approval of the current project was approved in the Deanship of Research and Graduate Studies at Mansoura University through under identification number R.26.05.3727.

Additional information

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