

Hematological and Metabolic Alterations Across Glycemic Categories in Patients with Type 2 Diabetes Mellitus

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Abstract

Background: Increasing evidence indicates that patients with type 2 diabetes mellitus (T2DM) are associated with alterations in several hematological parameters, besides having metabolic disorders that may be associated with glycated hemoglobin (HbA1c).

Aim: This study aimed to assess differences in hematological and metabolic parameter variations in T2DM patients across different glycated hemoglobin (HbA1c) levels and to examine the relationship between HbA1c levels and specific metabolic and hematological markers.

Materials and Methods: The conducted among 80 participants, including 20 healthy controls and 60 patients with type 2 diabetes mellitus. The diabetic participants were categorized according to HbA1c levels into three groups: 6.6–7.0%, 7.1–9.0%, and >9.1%, with 20 participants in each group. BMI, lipid profile parameters, and selected hematological indices were assessed and analyzed statistically.

Results: All variables showed significant differences between the patient and control groups ($p < 0.001$). HbA1c differed significantly among the four groups ($p < 0.001$). Metabolic profile: BMI, total cholesterol, triglycerides, and LDL-C increased significantly with increased HbA1c; HDL-C decreased in the same way ($p < 0.001$). Hematological parameters differed significantly in RBC count, hemoglobin, hematocrit, MCH, and MCHC ($p < 0.001$). Compared with controls, diabetic groups generally exhibited lower RBC count, hemoglobin, hematocrit, and MCH, whereas MCHC increased progressively with HbA1c. Most pairwise comparisons were significant, although some differences in RBC count, hemoglobin, and MCH were not significant between selected groups. Increasing HbA1c levels were associated with significant metabolic and hematological alterations in T2DM.

Conclusion: These findings show that hematological and metabolic parameters varied across increasing glycated hemoglobin (HbA1c) groups in patients with type 2 diabetes mellitus. Higher HbA1c levels were significantly associated with changes in lipid profile and hematological indices, mainly increased total cholesterol, LDL-C, and triglyceride levels, along with lower HDL-C and hemoglobin-related parameters.

Keywords: HbA1c; Type 2 diabetes mellitus; Hematological parameters; Metabolic profile.

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Introduction

Type 2 diabetes mellitus (T2DM) has a progressive impairment of insulin action and β -cell function, resulting in persistent hyperglycemia and substantial risks of microvascular and macrovascular complications [1]. T2DM represents the major form of diabetes and constitutes an increasing worldwide public-health problem; its growing prevalence is linked with challenges in early diagnosis and long-lasting disease management [2]. Chronic hyperglycemia causes various problems in the body, including vascular, renal, neural, and ocular damage, making evaluation of glycemic levels vital for preventing and monitoring diabetes-related complications [3].

Glycated hemoglobin (HbA1c) is a recognized indicator of chronic glycemic exposure and reflects average blood glucose levels over approximately the preceding 2–3 months [4]. According to the American Diabetes Association (ADA), an HbA1c level of $\geq 6.5\%$ can be used to diagnose diabetes mellitus; a prediabetes HbA1c level ranges between 5.7% and 6.4%. Its importance lies in its moderately low biological variability, good pre-analytical stability, and no fasting requirement, which is valuable for diagnosing and controlling diabetes [5,6].

Chronic hyperglycemia is linked to variations in fat metabolism via insulin resistance, increased lipolysis, and increased liver production of low-density lipoproteins (LDL) [7]. Nevertheless, study results remain unreliable regarding the relations between HbA1c levels and lipid parameters [8-10]. Glycated hemoglobin was correlated with cholesterol and triglyceride levels, and glycemic control was strongly associated with dyslipidemia [9].

However, Glycated hemoglobin is affected by serum glucose and by factors that influence red blood cell (RBC) lifespan and turnover, as well as hemoglobin (Hb) features [11]. Accordingly, anemia, hemoglobinopathies, hemolysis, and altered erythrocyte turnover can alter the association between HbA1c and real glycemic control [6,12]. These changes may reflect chronic hyperglycemia, oxidative stress, inflammation, altered erythrocyte physiology, and other diabetes-associated metabolic disturbances. The relationship between HbA1c and specific hematological parameters remains incompletely characterized, and findings vary across populations and parameters [13,14].

This study aimed to assess differences in hematological and metabolic parameter variations in T2DM patients across different glycated hemoglobin (HbA1c) levels and to examine the relationship between HbA1c levels and specific metabolic and hematological markers.

Materials and Methods

A. Patients and control groups

This observational case-control research was conducted at Baghdad Teaching Hospital among visiting patients from June to September 2026. The study included 80 subjects: 60 patients aged 45–64 years who were recently diagnosed with type 2 diabetes using the American Diabetes Association (ADA) criteria [6]. The control group consisted of 20 subjects from the same hospital with negative diabetes tests, matched on age, gender, and all information in the case sheet with the study patients. Subjects were separated into 4 groups: the control group (group 1) and three groups based on HbA1c% level: group 2 (6.6–7%), group 3 (7.1–9%), and group 4 ($>9.1\%$).

B. Ethical statement

The College of Dentistry at the University of Baghdad approved the study through the Ethics Committee (reference number 1229 in 2026), and the study complied with the World Medical Association's Declaration of Helsinki.

C. Sample collection

Venous blood samples were collected from patients and control participants after 10–12 hours of fasting. Approximately 4 mL of blood was drawn from each participant under aseptic conditions during routine hospital procedures and transported into clot activator tubes. The specimens were then centrifuged at 3000 rpm for 5 minutes, after which the serum was separated, divided into equal aliquots, and stored at $-20\text{ }^{\circ}\text{C}$ until subsequent laboratory analyses.

D. Exclusion criteria

Patients on lipid-lowering drugs, as well as those with cardiovascular disease, endocrine abnormalities, poor liver function, renal difficulties, and mental illnesses were also excluded.

E. Sample size

Sample size was calculated with the G*Power program 3.1.9.7 with One-way ANOVA for four groups (three groups of T2DM patients and a control group) at alpha error (α) 0.05, power ($1-\beta$) 0.80; a total sample size of 76 contributors was found to be acceptable to detect a medium-to-large effect size (f) 0.40. Our study included 80 subjects, demonstrating that the sample size was adequate for this investigation [15].

F. Study Variables

The independent variable was HbA1c levels, and the dependent variables were diabetic patients' lipid profiles, including total cholesterol (TC), high-density lipoprotein cholesterol (HDL-c), low-density lipoprotein cholesterol (LDL-c), and triglycerides (TG), which were measured using an automated clinical chemistry analyzer (cobas c 311), Roche Diagnostics, Switzerland. Other patients' hematological parameters, including red blood cell count (RBC), hemoglobin (Hb), hematocrit (HCT), mean corpuscular hemoglobin (MCH), and mean corpuscular hemoglobin concentration (MCHC), were measured using an automated hematology analyzer (Sysmex XN-1000), Sysmex Corporation, Japan. Body mass index (BMI) was estimated from a person's weight, adjusted for height, using basic anthropometric measurements [16].

H. Statistical analysis

Statistical analysis was performed using the Statistical Package for the Social Sciences (SPSS, version 22.0; IBM Corp., Armonk, NY, USA). Continuous variables were expressed as mean $\pm$ standard deviation (SD) and compared between groups by an independent-samples t-test, and categorical variables were expressed as frequencies and percentages and compared between groups using chi-square. Differences in variable means across the four study groups (control and patient groups) using One-Way Analysis of Variance (ANOVA), followed by Tukey's post-hoc test for pairwise comparisons between groups. The associations between HbA1c and BMI, lipid profile, and hematological parameters were evaluated using Spearman's rank correlation coefficient (ρ), as appropriate. Statistical significance was established at $p < 0.05$, and highly significant differences were defined at $p < 0.001$.

Results

The study included 80 subjects, 60 patients with type 2 diabetes mellitus and 20 healthy controls. Table 1 demonstrates the demographic, metabolic, and hematological characteristics of patients compared with the control group. Gender distribution (assessed using the chi-square test) did not differ significantly between the patient and control groups ($\chi^2 = 0.018$, $p = 0.895$). An independent t-test showed that mean age was 55.25 ± 5.39 years in patients and 54.25 ± 4.22 years in controls, with no significant difference between the Patient and Control groups ($p = 0.454$).

Patients with T2DM had significantly higher HbA1c, BMI, total cholesterol, LDL-C, and triglycerides than controls ($p < 0.001$), while HDL-C was significantly lower than in controls. In contrast, hematological parameters, including RBC count, hemoglobin, MCH, and HCT, were significantly lower in patients with T2DM than in controls ($p < 0.001$). Conversely, MCHC was significantly higher in patients with T2DM than controls ($p < 0.001$).

Table 1. Demographic, metabolic, and hematological characteristics of patients with T2DM and control participants

Variable (Mean $\pm$ SD)	Control group (n=20)	T2DM Patients group (n=60)	Test Statistic	P- value
Male	13 (65.0%)	36 (60.0%)	$\chi^2=0.018$ (Chi-square test)	0.895
Female	7 (35.0%)	24 (40.0%)		
Age (years)	54.25 $\pm$ 4.22	55.25 $\pm$ 5.39	t= 0.753	0.454
HbA1c %	5.24 $\pm$ 0.58	8.49 $\pm$ 1.61	t=13.26	<0.001

BMI (Kg/m²)	26.62± 0.38	27.91± 1.60	t=5.79	<0.001
Total Cholesterol (mg/dL)	172.25± 8.03	238.83± 11.40	t=28.69	<0.001
TG (mg/dL)	83.60± 8.43	169.25± 9.86	t=34.80	<0.001
HDL-C (mg/dL)	65.40 ± 3.41	48.25± 2.73	t=9.08	<0.001
LDL-C (mg/dL)	77.40± 6.75	119.05± 6.61	t=24.28	<0.001
RBC count (μL/10^{x6})	6.44± 0.13	5.36± 0.16	t= -11.69	<0.001
Hb (g/dL)	14.45± 0.28	11.20± 0.36	t= -36.37	<0.001
MCH (pg)	27.46± 0.46	25.95± 0.48	t= -12.38	<0.001
MCHC (g/dL)	32.55± 0.53	35.89± 0.72	t= 18.97	<0.001
HCT%	45.15± 0.63	36.55± 1.66	t= -22.53	<0.001

Values are expressed as mean ± standard deviation (Mean ± SD); significant p-value <0.001**, highly significant (HS); using Chi-square test for gender and t- test for other variables

Table 2 compares metabolic and hematological parameters across the four study groups. The groups included a control group (Group 1, n = 20) and participants with HbA1c levels of 6.6–7.0% (Group 2, n = 20), 7.1–9.0% (Group 3, n = 20), and >9.1% (Group 4, n = 20). HbA1c differed significantly across the groups, with mean values of $5.24 \pm 0.58\%$, $6.79 \pm 0.16\%$, $8.20 \pm 0.61\%$, and $10.48 \pm 0.61\%$ in Groups 1–4, respectively ($F = 357.51$, $p < 0.001$). BMI also differed significantly among the groups ($F = 215.18$, $p < 0.001$), with mean values of 26.62 ± 0.38 , 26.18 ± 0.46 , 29.72 ± 0.18 , and 27.84 ± 0.71 kg/m², respectively. Significant differences between groups were also observed for all assessed lipid parameters. Total cholesterol increased from 172.25 ± 8.02 mg/dL in the control group to 220.00 ± 1.09 , 230.00 ± 1.32 , and 240.00 ± 1.32 mg/dL in Groups 2, 3, and 4, respectively ($F = 1138.45$, $p < 0.001$). Similarly, triglyceride (TG) concentrations were 83.60 ± 8.43 , 158.10 ± 4.73 , 169.80 ± 3.37 , and 179.85 ± 4.32 mg/dL across Groups 1–4, respectively ($F = 1239.61$, $p < 0.001$). HDL concentrations were decreased significantly from control compared with patient groups 65.40 ± 3.41 , 59.35 ± 3.25 , 52.30 ± 3.64 , and 48.25 ± 2.73 mg/dL, respectively ($F = 108.62$, $p < 0.001$), while LDL concentrations were 77.40 ± 6.75 , 111.65 ± 4.20 , 120.25 ± 3.00 and 120.25 ± 22.16 mg/dL, respectively ($F = 47.96$, $p < 0.001$).

Hematological parameters also differed significantly among the four groups overall. Mean RBC counts were 5.43 ± 0.13 , 5.03 ± 0.16 , 4.89 ± 0.16 , and $4.97 \pm 0.15 \times 10^6/\mu\text{L}$ in Groups 1–4, respectively ($F = 50.84$, $p < 0.001$). Mean hemoglobin concentrations were 14.46 ± 0.28 , 11.28 ± 0.35 , 11.44 ± 0.26 and 10.87 ± 0.20 g/dL, respectively ($F = 703.11$, $p < 0.001$), while hematocrit values were $45.15 \pm 0.63\%$, $38.50 \pm 0.84\%$, $36.27 \pm 0.49\%$ and $34.89 \pm 0.82\%$, respectively ($F = 821.35$, $p < 0.001$). MCH values were 27.46 ± 0.57 , 26.05 ± 0.41 , 25.91 ± 0.44 , and 25.90 ± 0.57 pg, respectively ($F = 45.26$, $p < 0.001$). In contrast, MCHC increased across the groups, with mean values of 32.55 ± 0.53 , 35.50 ± 0.63 , 35.82 ± 0.64 , and 36.28 ± 0.69 g/dL, respectively ($F = 141.22$, $p < 0.001$).

Table 2. Comparison of baseline clinical, biochemical, and hematological parameters across study groups with ANOVA test

Measured variable	Group 1 Control	Group 2 (HbA1c levels of 6.6-7%)	Group 3 (HbA1c levels of 7.1-9 %)	Group 4 (HbA1c levels of >9.1%)	F-value (3.76)	P-value
HbA1c %	5.24 ± 0.58	6.79 ± 0.16	8.20 ± 0.61	10.48 ± 0.61	357.51	<0.001**
BMI (Kg/m²)	26.62±0.38	26.18± 0.46	29.72± 0.18	27.84± 0.71	215.18	<0.001**
Total Cholesterol (mg/dL)	172.25±8.02	220.00±1.09	230.00±1.32	240.00±1.32	1138.45	<0.001**
TG (mg/dL)	83.60±8.43	158.10±4.73	169.80±3.37	179.85±4.32	1239.61	<0.001**
HDL-C (mg/dL)	65.40±3.41	59.35± 3.25	52.30± 3.64	48.25± 2.73	108.62	<0.001**
LDL-C (mg/dL)	77.40±6.75	111.65±4.20	120.25±3.00	120.25±22.16	47.96	<0.001**
RBC count (μL/10^{x6})	5.43±0.13	5.03± 0.16	4.89± 0.16	4.97± 0.15	50.84	<0.001**
Hb (g/dL)	14.46±0.28	11.28± 0.35	11.44± 0.26	10.87± 0.20	703.11	<0.001**
MCH (pg)	27.46±0.57	26.05± 0.41	25.91± 0.44	25.90± 0.57	45.26	<0.001**
MCHC (g/dL)	32.55±0.53	35.50±0.63	35.82±0.64	36.28±0.69	141.22	<0.001**
HCT%	45.15±0.63	38.50± 0.84	36.27± 0.49	34.89± 0.82	821.35	<0.001**

Values are expressed as mean ± standard deviation (Mean ± SD); significant p-value <0.001**, highly significant (HS); All differences among four groups assessed using one-way ANOVA test

Post-hoc analysis (Table 3) displayed significant differences between the study groups for most inspected parameters. HbA1c, total cholesterol, and triglycerides differed significantly across all pairwise group comparisons, indicating substantial differences across glycemic categories. BMI did not differ significantly between group 1 and group 2, but other comparisons showed significant differences. HDL-C decreased significantly ($p<0.001$) across most groups with different HbA1c levels, with smaller differences between groups 3 and 4.

For hematological parameters, RBC count, hemoglobin, MCH, MCHC, and HCT differed significantly between the control group and all diabetic groups (group 1 vs groups 2, 3, and 4), while some comparisons among the diabetic groups were not significant. Overall, the post-hoc analysis identifies the exact group comparisons responsible for the significant differences detected by one-way ANOVA.

Table 3. Tukey post-hoc multiple comparisons among the study groups

Parameter	Group 1 vs Group 2	Group 1 vs Group 3	Group 1 vs Group 4	Group 2 vs Group 3	Group 2 vs Group 4	Group 3 vs Group 4
HbA1c	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
BMI	0.102	<0.001	<0.001	<0.001	<0.001	<0.001
Total cholesterol	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
HDL-C	<0.001	<0.001	<0.001	<0.001	<0.001	=0.001
LDL-C	<0.001	<0.001	<0.001	<0.001	<0.001	0.004
Triglycerides	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
RBC count	<0.001	<0.001	<0.001	0.015	0.453	0.391
Hemoglobin	<0.001	<0.001	<0.001	0.301	<0.001	<0.001
MCH	<0.001	<0.001	<0.001	0.805	0.750	0.100
MCHC	<0.001	<0.001	<0.001	0.389	<0.001	0.101
HCT	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Adjusted p-values were obtained using Tukey's honestly significant difference (HSD) post-hoc test following one-way ANOVA.

Table 4 reported the correlation analysis, which demonstrated significant associations between HbA1c and numerous biochemical and hematological parameters among patients with T2DM. HbA1c showed a moderate positive relationship with BMI ($\rho = 0.454$, $p < 0.001$). HbA1c showed strong positive correlations with total cholesterol ($\rho = 0.845$, $p < 0.001$) and LDL-C ($\rho = 0.830$, $p < 0.001$). The strongest positive association was observed with triglycerides ($\rho = 0.893$, $p < 0.001$). while HDL-C correlate negatively ($\rho = -0.854$, $p < 0.001$) with HbA1c.

Concerning hematological parameters, HbA1c demonstrated a moderate negative correlation with Hb ($\rho = -0.434$, $p < 0.001$) and a strong negative correlation with HCT ($\rho = -0.865$, $p < 0.001$). MCHC showed a significant positive correlation with HbA1c ($\rho = 0.396$, $p = 0.002$). However, RBC count ($\rho = -0.136$, $p = 0.298$) and MCH ($\rho = -0.071$, $p = 0.591$) were not significantly correlated with HbA1c.

Table 4. Spearman correlations between HbA1c and selected clinical, biochemical, and hematological parameters among patients with type 2 diabetes mellitus (n=60)

Variable	Spearman's ρ	P-value	Interpretation
BMI	0.454	<0.001	Moderate positive correlation
Total cholesterol	0.845	<0.001	Strong positive correlation
HDL-C	-0.854	<0.001	Strong negative correlation
LDL-C	0.830	<0.001	Strong positive correlation
Triglycerides	0.893	<0.001	Very strong positive correlation
RBC count	-0.136	0.298	No significant correlation
Hemoglobin	-0.434	<0.001	Moderate negative correlation
MCH	-0.071	0.591	No significant correlation
MCHC	0.396	0.002	Significant positive correlation

HCT	−0.865	<0.001	Strong correlation	negative
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Spearman's rank correlation coefficient was used to assess the association between HbA1c and the investigated variables among patients with type 2 diabetes mellitus. A two-tailed p-value <0.05 was statistically significant.

Discussion

This study showed significant differences in several metabolic and hematological parameters across glycemic categories among patients with type 2 diabetes mellitus (T2DM). HbA1c increased progressively from the control group to groups with higher levels of glycemic abnormality, confirming its usefulness as an indicator of chronic glycemic exposure. The American Diabetes Association (ADA) recognizes HbA1c as a primary examination of glycemic status and observes that it reflects normal glycemia over about 2–3 months [6,17]. The significant differences in HbA1c among the study groups therefore support using HbA1c-based categories to inspect metabolic and hematological variations across different gradations of glycemic control.

Glycemic control and BMI

Body mass index (BMI) was pointedly higher in groups with higher HbA1c levels than in the control group. In particular, group 3 (HbA1c 7.1–9.0%) showed the greatest mean BMI. Additionally, correlation analysis among T2DM patients demonstrated a remarkable positive relationship between HbA1c and BMI. These results agree with Deng *et al.* (2025), who found the same correlation in patients with T2DM; obese patients had higher HbA1c levels ($8.5 \pm 1.3\%$) than normal individuals [18].

Our findings confirmed results from several studies, showing an association between higher BMI and increased HbA1c because increased fat tissue, mainly visceral fat, has adverse metabolic effects [19,20]. This supports the idea that higher BMI contributes to increased insulin resistance and reduced insulin activity (20).

The observed relationship between BMI and HbA1c in this study aligns with previous evidence. Kodama *et al.* (2014) found that people with higher BMI tended to have higher HbA1c values and proposed that excess adipose tissue may impair glycemic regulation by causing insulin resistance [21]. Likewise, Viigimaa *et al.* (2020) found an association between elevated BMI and higher HbA1c among patients with T2DM, suggesting that excess adipose tissue may contribute to sustained hyperglycemia by impairing insulin sensitivity [22]. Furthermore, Blüher (2023) emphasized the role of visceral fat tissue in the progression of insulin resistance, which may later contribute to inadequate glycemic control [20].

Lipid profile and HbA1c

Lipid parameters varied markedly across HbA1c categories. Total cholesterol, LDL-C, and triglycerides increased significantly, while HDL-C decreased significantly with higher glycemic categories. Correlation analysis showed strong positive associations between HbA1c and total cholesterol, LDL-C, and triglycerides, while there was a negative correlation with HDL-C.

These results align with Sharahili *et al.* (2023), who reported significantly increased triglycerides and total cholesterol with elevated HbA1c, along with a link between HbA1c and these parameters [9]. Ozder (2014) also reported higher serum levels of total cholesterol, triglycerides, and LDL-c in patients with diabetes than normal values [23]. Our findings also agree with previous studies reporting a notable correlation in T2DM patients between glycated hemoglobin and one or more lipid profile parameters [24,25]. Hussain *et al.* (2017) found unfavorable lipid parameters among T2DM patients with poor glycemic control. Those with HbA1c levels above 7.0% had notably higher total cholesterol and LDL-C than those with HbA1c of 7.0% or below; HbA1c was associated with several lipid parameters, but the relationship with HDL-C was negative and not significant [26]. AlZeer *et al.* (2025) also showed that HbA1c correlates significantly with TG levels, but that HDL-C and HbA1c are negatively correlated. However, some parameters, such as LDL-C and total cholesterol, showed no significant differences; significant associations were reported between HbA1c and triglycerides and HDL-C, supporting the relationship between glycemic control and lipid metabolism [27].

The association between hyperglycemia and lipid abnormalities results from multiple pathophysiologic mechanisms. Insulin resistance increases lipolysis, raises free fatty acid levels, increases LDL production in the liver, and reduces LDL clearance, leading to an atherogenic lipid profile. Poor glycemic control is often

accompanied by progressive weakening of lipid metabolism [28]. Many factors in DMT2 may affect blood lipid levels because carbohydrate and lipid metabolism are interrelated. Therefore, any disorder in carbohydrate metabolism disrupts lipid metabolism and inversely [29] (Haffner *et al.*, 2000).

Hematological parameters and HbA1c

The current study identified significant differences in several hematological indices across glycemic categories. RBC count, hemoglobin, MCH, and HCT were generally lower among T2DM patients than in the controls, but MCHC was higher. Importantly, HbA1c correlated significantly and negatively with hemoglobin and HCT. HbA1c also correlated significantly and positively with MCHC, but not with RBC count or MCH.

Adane *et al.* (2020) found results aligned with ours; they reported lower RBC count and Hb in the DM group than in controls, and MCHC values were markedly higher in the DM group [30]. Another study by Mayank Kumar *et al.* (2026) reported that Hb, RBC count, and hematocrit descend gradually with increasing HbA1c categories. Patients with HbA1c $\geq 6.5\%$ had significantly lower hemoglobin than controls. HbA1c showed a notably negative association with Hb, RBC count, and hematocrit; higher HbA1c levels were associated with lower RBC and Hb levels. MCH and MCHC also showed weak to moderate negative relationships, suggesting that exacerbated glycemic control may be related to microcytic and hypochromic variations [31]. Arkew *et al.* (2022) found that patients with T2DM had markedly lower RBC counts, Hb levels, and hematocrit values compared with controls, with an inverse association between glycemic status and hematological parameters; however, MCHC was significantly elevated among diabetic patients [32]. Nevertheless, other studies, contrary to ours, reported higher RBC counts and Hb levels in those with T2DM [33,34].

The relationship between HbA1c and erythrocyte characteristics matters because HbA1c forms through non-enzymatic glycation of hemoglobin, and the duration of erythrocyte exposure to glucose influences accumulated glycation. Shortened or prolonged RBC survival can lower or increase HbA1c, respectively, independent of glucose concentration [35]. RBC lifespan also varies between individuals, introducing biological variation into HbA1c interpretation [36]. Persistent hyperglycemia promotes oxidative stress and nonenzymatic glycation of hemoglobin and erythrocyte membrane proteins, reducing RBC deformability, enhancing cellular aggregation, accelerating erythrocyte senescence, and shortening RBC lifespan [37,38]. Thus, elevated MCHC in DM patients may reflect structural and functional alterations in erythrocytes associated with prolonged hyperglycemia. Increased Hb binding to the inner surface of the RBC membrane may contribute to spherocytic morphology and modify the mechanical characteristics of these cells [39]. This may result in spherocytic cell formation and alter RBC mechanical properties. Additionally, hemoglobin attached to the spectrin network increases RBC intracellular viscosity, which affects MCHC [40].

This study's originality lies in examining lipid and hematological changes across different levels of glycemic dysregulation in Iraqi patients with type 2 diabetes mellitus. Although prior studies have evaluated associations between HbA1c and lipid profiles and hematological parameters separately, fewer studies have examined interrelationships between erythrocyte indices and distinct lipid parameters within the same T2DM patients. Additionally, categorized HbA1c-defined glycemic groups allow evaluation of notable metabolic and hematological alterations by grade of glycemic dysregulation.

Limitation

Further studies with larger sample sizes and longer longitudinal follow-up, including more extensive tests, are recommended to explain the mechanisms and the clinical implications of these associations.

Conclusion

These findings show that hematological and metabolic parameters varied across increasing glycated hemoglobin (HbA1c) groups in patients with type 2 diabetes mellitus. Higher HbA1c levels were significantly associated with changes in lipid profile and hematological indices, mainly increased total

cholesterol, LDL-C, and triglyceride levels, along with lower HDL-C and hemoglobin-related parameters.

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