

Effect of yoga on glycemic control and inflammation in type 2 diabetes mellitus: a prospective non-randomized comparative interventional study.

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Abstract

Background:

Type 2 diabetes mellitus (T2DM) is characterized by persistent metabolic disturbance, insulin resistance, and a low-grade inflammatory state. Yoga may complement standard treatment by combining physical activity, breathing practices, relaxation, and stress regulation.

Objectives:

To evaluate changes in glycemic indices, insulin resistance, and selected inflammatory markers during a structured 45-day yoga program in patients with T2DM receiving routine medication.

Methods:

This prospective, non-randomized comparative interventional study included 100 adults with established T2DM attending the General Medicine outpatient department. Fifty participants continued routine antidiabetic medication alone, while 50 received the same routine treatment together with a supervised 60-minute yoga session daily for 45 days. Venous blood was collected on days 0, 15, 30, and 45 for fasting blood sugar (FBS), HbA1c, insulin, HOMA-IR, high-sensitivity C-reactive protein (hsCRP), interleukin-1 β (IL-1 β), and interleukin-6 (IL-6).

Results: The study included 100 adults with T2DM, with 50 participants in each group. The mean age was 52.2 ± 4.96 years in the control group and 53.1 ± 5.9 years in the yoga group; the mean duration of diabetes was 6.0 ± 1.85 and 5.5 ± 1.42 years, respectively. All participants were receiving oral hypoglycemic drugs. Over 45 days, the yoga group showed significant improvement in all measured metabolic and inflammatory variables (follow-up $p < 0.01$). By day 45, mean FBS was 131.20 ± 23.18 mg/dL, HbA1c $6.21 \pm 0.80\%$, insulin 9.89 ± 1.82 μ IU/mL, HOMA-IR 3.09 ± 0.67 , hsCRP 18.3 ± 2.99 nmol/L, IL-1 β 25.14 ± 2.48 pg/mL, and IL-6 3.35 ± 1.49 pg/mL.

Conclusion:

A 45-day supervised yoga program, when added to routine medication, was associated with better glycemic control, lower insulin resistance, and reduced inflammatory marker levels in patients with T2DM.

Recommendations:

Yoga can be considered as a supportive component of diabetes care for suitable patients. Longer studies with clearly defined allocation procedures and broader lifestyle assessment are warranted.

Keywords: Yoga; Type 2 diabetes mellitus; Insulin resistance; HbA1c; hsCRP; IL-6; IL-1 β

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Introduction

Type 2 diabetes mellitus (T2DM) is a chronic metabolic disorder characterized by persistent hyperglycemia resulting mainly from insulin resistance, together with a gradual decline in pancreatic β -cell function. It represents the predominant form of diabetes worldwide and contributes substantially to cardiovascular disease, renal impairment, neuropathy, retinopathy, and other long-term complications. The increasing prevalence of T2DM has been closely associated with rapid urbanization, sedentary lifestyles, changes in dietary habits, increasing obesity, and underlying genetic susceptibility [1]. Although abnormalities in glucose metabolism remain central to the disease, growing evidence indicates that T2DM is also accompanied by a state of chronic, low-grade systemic inflammation. This inflammatory environment may further reduce insulin sensitivity and contribute to the progression of metabolic and vascular complications.

Inflammatory mediators have therefore gained considerable attention in understanding the pathophysiology of T2DM. Cytokines and acute-phase proteins, including interleukin-6 (IL-6) and C-reactive protein, have been associated with insulin resistance and impaired glucose homeostasis [3,4]. IL-6 is produced by several tissues, including adipose tissue and immune cells, and persistent elevation of this cytokine may reflect ongoing metabolic inflammation. Interleukin-1 β (IL-1 β) also appears to have an important role in pancreatic β -cell dysfunction. Prolonged exposure to elevated glucose concentrations may activate inflammatory pathways within pancreatic islets and stimulate IL-1 β production, leading to β -cell stress, reduced insulin secretion, and progressive deterioration of glycemic control [5]. These findings suggest that interventions capable of reducing both metabolic abnormalities and inflammatory activity may provide additional benefit in the management of T2DM.

Lifestyle modification remains an important component of diabetes management in addition to pharmacological therapy. Regular physical activity, dietary modification, weight control, and stress reduction can improve insulin sensitivity and assist in maintaining better glycemic control. Yoga has increasingly been considered as a complementary lifestyle intervention because it combines physical postures, controlled breathing, relaxation, and meditative practices within a single structured program. Unlike conventional physical exercise alone, yoga may influence metabolic health through a combination of muscular activity, improved autonomic balance, reduction in psychological stress, and modulation of neuroendocrine responses.

Previous studies involving patients with diabetes have reported improvements in fasting blood glucose, glycated hemoglobin, circulating insulin concentrations, and other

metabolic parameters following regular yoga practice [6,8-10]. Improvements in psychological well-being, perceived stress, physical flexibility, and general quality of life have also been described. Since psychological stress can activate sympathetic and hypothalamic-pituitary-adrenal pathways and adversely influence glucose metabolism, the relaxation and breathing components of yoga may complement the metabolic benefits derived from physical activity. Yoga may therefore have potential value as an adjunct to standard medical treatment rather than as a substitute for prescribed antidiabetic therapy.

Although several studies have examined the effect of yoga on glycemic indices in individuals with T2DM, relatively fewer studies have simultaneously evaluated its influence on insulin resistance and circulating inflammatory markers over repeated follow-up intervals. Studying metabolic and inflammatory variables together may provide a broader understanding of the possible physiological changes associated with regular yoga practice.

The present study was therefore undertaken to evaluate the effect of a structured 45-day yoga program, provided in addition to routine antidiabetic medication, on glycemic control, insulin resistance, and inflammatory status in patients with T2DM. Changes in fasting blood glucose, glycated hemoglobin, fasting insulin, HOMA-IR, high-sensitivity C-reactive protein (hsCRP), IL-6, and IL-1 β were assessed at predefined intervals during the study period. In addition, the relationship between HOMA-IR and selected glycemic and inflammatory parameters was examined to determine whether changes in insulin resistance were associated with corresponding alterations in metabolic or inflammatory status.

MATERIALS AND METHODS

Study Design

This was a prospective, non-randomized, comparative interventional study with repeated-measures follow-up over 45 days. Participants receiving routine antidiabetic medication alone served as the control group, whereas those receiving routine medication plus the structured yoga program constituted the intervention group. The same participants were assessed at baseline and again on days 15, 30, and 45.

Study Setting and Period

The study was conducted from October 2017 to February 2020 at GITAM Institute of Medical Sciences & Research (GIMSR), GITAM (Deemed to be University), Visakhapatnam, Andhra Pradesh, India. Participants were recruited through the General Medicine outpatient

department, and the scheduled clinical assessments, supervised yoga sessions, venous blood collection, and biochemical investigations were carried out within the institutional clinical and laboratory facilities. The setting enabled coordinated medical follow-up and repeated laboratory assessment at the predefined study visits.

Recruitment of Study Subjects

A total of 100 adults with type 2 diabetes mellitus (T2DM) attending the General Medicine outpatient department were enrolled after clinical evaluation and eligibility assessment. Participants were allocated to two groups of 50 according to participation in the structured yoga program. All participants continued their prescribed antidiabetic treatment throughout the study period.

The control group consisted of 50 patients with T2DM who were receiving routine medical treatment but were not participating in the yoga program. The yoga group included 50 patients with T2DM who were receiving medical treatment and additionally participated in a structured 45-day yoga program. The yoga sessions were conducted for approximately 60 minutes each day under the supervision of a certified yoga instructor. The program was based on the recommendations of the Ministry of AYUSH, Government of India. Participants were familiarized with the exercises before commencing the intervention, and the practices were introduced progressively according to their level of difficulty and ability to perform them comfortably.

Ethics

The study was initiated after obtaining approval from the Institutional Ethics Committee under approval number GIMSR/College/028-A/3 01/1. Before enrolment, each participant was informed about the purpose of the study, the procedures involved, the schedule of blood collection, and the nature of the yoga intervention. Written informed consent was obtained from all participants before any study-related procedure was undertaken. Participation was voluntary, and the confidentiality of personal and laboratory information was maintained throughout the study.

Sample Size Calculation

The sample size was estimated for comparison of the two independent study groups. Assuming a two-sided significance level of 5%, a statistical power of 80%, and a standardized effect size of approximately 0.60 for the expected difference in metabolic and inflammatory parameters between the groups, the required number of participants was calculated using the formula:

$$n = 2 (Z\alpha/2 + Z\beta)^2 / d^2$$

where $Z\alpha/2$ was 1.96 for a 95% confidence level, $Z\beta$ was 0.84 for 80% power, and d represented the standardized effect size. The calculation yielded approximately 44 participants per group. After allowing for an anticipated attrition or incomplete follow-up rate of approximately 10%, the target sample was increased to about 49 participants per group and rounded to 50 participants in each group. Thus, a total sample size of 100 participants was included in the study. The longitudinal collection of measurements at four time points further allowed assessment of both within-group changes and differences in response between the two groups.

Exclusion Criteria

Participants with factors that could independently influence metabolic, endocrine, or inflammatory markers were excluded. Chronic alcohol users and chronic smokers were not included in the study. Individuals receiving treatment for hypertension or thyroid disorders were also excluded. Patients with known immunological disorders or psychiatric illnesses requiring medication were not considered eligible. These exclusion criteria were applied to minimize potential confounding of biochemical and inflammatory measurements and to obtain a more comparable study population.

Sample Collection

Approximately 10 mL of venous blood was collected from each participant at four predefined time points: baseline (day 0), day 15, day 30, and day 45 [6]. Blood samples were collected under aseptic conditions and distributed into appropriate collection tubes according to the requirements of the individual biochemical and immunological assays. Fasting samples were obtained for the estimation of fasting blood glucose and insulin. Samples required for HbA1c, hsCRP, insulin, IL-6, and IL-1 β measurements were processed according to the requirements of the respective analytical methods. The same sampling schedule was followed in both the yoga and control groups to permit comparison of temporal changes during the 45-day study period.

Yoga Program

Participants allocated to the yoga group underwent a structured 45-day yoga intervention based on the program recommended by the Ministry of AYUSH, Government of India [1,7]. Each supervised session lasted approximately 60 minutes per day and was conducted by a certified yoga instructor. The program comprised the yoga practices specified in Supplementary Table 1, including the relevant

physical postures, breathing practices, relaxation techniques, and other components included in the prescribed protocol.

The yoga practices were introduced gradually to ensure that participants became familiar with the correct posture, breathing pattern, and sequence of movements. Simpler practices were taught initially, followed by progressively more demanding asanas according to the participant's ability and comfort. Particular attention was given to correct performance and avoidance of excessive physical strain. The intervention was continued for 45 consecutive days, while participants in the control group continued their usual medical management without participating in the structured yoga sessions.

Estimation of Biochemical Parameters

Fasting blood glucose was measured by the hexokinase method, while glycated hemoglobin (HbA1c) and high-sensitivity C-reactive protein (hsCRP) were estimated using immunoturbidimetric methods. These parameters were analyzed using commercially available reagents on the Roche cobas c311 automated clinical chemistry analyzer according to the manufacturer's instructions.

Serum insulin concentration was determined by an electrochemiluminescence immunoassay using the Roche cobas e411 immunoassay analyzer. Insulin resistance was assessed using the Homeostatic Model Assessment of Insulin Resistance (HOMA-IR). When fasting glucose was expressed in mmol/L, HOMA-IR was calculated as:

$$\text{HOMA-IR} = [\text{Fasting insulin } (\mu\text{U/mL}) \times \text{Fasting glucose (mmol/L)}] / 22.5$$

When fasting glucose values were expressed in mg/dL, the corresponding equation was:

$$\text{HOMA-IR} = [\text{Fasting insulin } (\mu\text{U/mL}) \times \text{Fasting glucose (mg/dL)}] / 405$$

Higher HOMA-IR values were interpreted as indicating greater insulin resistance.

Interleukin Assay

Serum concentrations of interleukin-6 (IL-6) and interleukin-1 beta (IL-1 β) were measured using a sandwich enzyme-linked immunosorbent assay (ELISA) supplied by PeproTech. The assays were carried out according to the manufacturer's protocol using the standards supplied with the respective kits.

For preparation of the calibration curve, the supplied cytokine standards were serially diluted in the recommended diluent to obtain the required range of concentrations, with a zero-standard or reagent blank included. A volume of 100 μL of each standard or test sample was added to the

appropriate microplate wells. Samples and standards were analyzed in triplicate to improve analytical reliability. The plate was incubated at room temperature for 2 hours and subsequently washed four times with the supplied wash buffer to remove unbound material.

After washing, 100 μL of the appropriate biotinylated detection antibody, diluted to a final concentration of 0.5 $\mu\text{g/mL}$ (500 ng/mL), was added to each well. The plate was incubated for a further 2 hours at room temperature and washed four times. Subsequently, 100 μL of diluted streptavidin-horseradish peroxidase conjugate, prepared at a dilution of 1:20,000, was added to each well and incubated for 30 minutes at room temperature.

Following another four washing cycles, 100 μL of TMB substrate solution was added to each well. Color development was allowed to proceed for approximately 20 minutes at room temperature. The enzymatic reaction was then stopped by adding 100 μL of 1 M HCl stop solution. Absorbance was measured at 450 nm, with wavelength correction at 620 nm, using a Bio-Rad microplate reader.

The ELISA reagents included the required TMB substrate, concentrated phosphate-buffered saline, assay diluent, wash buffer, mouse anti-human capture antibodies, biotinylated goat anti-human detection antibodies, recombinant human IL-6 and IL-1 β standards, and streptavidin-HRP conjugate. Cytokine concentrations in the study samples were calculated from the respective standard curves according to the manufacturer's instructions.

Measures to Address Potential Bias

Several measures were taken to reduce potential bias. The same eligibility criteria were applied to both groups to limit clinical heterogeneity and reduce confounding from conditions likely to influence metabolic or inflammatory markers. Blood samples were obtained under the same fasting conditions and according to the same day 0, 15, 30, and 45 schedule in both groups. Biochemical measurements were performed using the same analyzers, reagents, and assay procedures throughout the study, while cytokine standards and samples were analyzed in triplicate to improve analytical reliability. The yoga intervention followed a standardized protocol and was supervised by a certified instructor to reduce variability in intervention delivery. Participants were not instructed to alter their usual diet or other lifestyle practices during the 45-day study period. Because allocation depended on participation in the yoga program rather than random assignment, selection bias and baseline imbalance could not be fully eliminated. This limitation was considered when interpreting between-group findings, with emphasis placed on longitudinal change and the group $\times$ time interaction.

Statistical Analysis

Data were entered, checked for completeness, and analyzed using SPSS software, Version 25. Continuous variables were summarized as mean and standard deviation when they followed an approximately normal distribution. The distribution of continuous variables was assessed before performing parametric statistical tests.

Baseline characteristics and biochemical parameters between the yoga and control groups were compared using the independent-samples Student's t-test for continuous variables where appropriate. Because the same participants were assessed repeatedly at baseline, day 15, day 30, and day 45, longitudinal changes were evaluated using a mixed-design repeated-measures analysis of variance (ANOVA). Time represented the within-subject factor, whereas study group represented the between-subject factor. The analysis

therefore examined the time effect, group effect, and particularly the group $\times$ time interaction, which indicated whether the pattern of change over the 45 days differed between participants practicing yoga and those receiving routine treatment alone.

The assumption of sphericity was assessed for repeated-measures analyses, and an appropriate correction, such as the Greenhouse-Geisser adjustment, was applied when this assumption was violated. When an overall ANOVA showed statistical significance, post-hoc comparisons with adjustment for multiple testing were performed to identify the time points responsible for the observed difference. All statistical tests were two-sided, and a $^{***}P$ value $<0.05^{***}$ was considered statistically significant.

The complete sequence of yoga practices and the time allocated to each component are presented in Supplementary Table 1.

Supplementary Table 1: Yoga Practices Used During the 45-Day Intervention

S. No.	Practice	Duration
1	Starting prayer: Asathoma Satgamaya	2 min
2	Preparatory sukshnavyayamas and shithililarana practices: Urdhvahasthashvasana; Kati-shakthi vikasaka; Sarwangapushti	6 min
3	Suryanamaskara: six rounds of 10-step fast Suryanamaskara and one round of 12-step slow Suryanamaskara; chair modification when required	9 min
4	Asanas: standing (Trikonasana, Pravritta Trikonasana, Prasaritha Padhasana); supine (Jataraparivartasana, Pavanamukthasana, Viparitarakani); prone (Bhujangasana, Dhanurasana followed by Pavanamukthasana); sitting (Mandukasana, Vakrasana/Ardhamatsyendrasana, Paschimotthanasana, Ardhastrasana); ending with supine abdominal-breathing relaxation	15 min
5	Kriya: Agnisara and Kapalbhata at 60 breaths/min for 1 minute followed by 1 minute of rest	3 min
6	Pranayama: Nadishuddhi for 6 minutes with brief antarkumbhaka and jalandhar bandha, followed by Bhramari for 3 minutes	9 min
7	Meditation for stress management and deep relaxation, primarily cyclic meditation; participants could use an established relaxation technique from their own institute	15 min
8	Resolve	1 min
9	Closing prayer: Sarvebhavanthu	1 min
	Total	60 min

SN = Suryanamaskara

Results

Baseline Sociodemographic and Clinical Characteristics

Participants were 45–60 years of age and were receiving oral hypoglycemic drugs. Baseline sociodemographic and clinical characteristics are summarized in Table 1.

Table 1: Baseline Sociodemographic and Clinical Characteristics of the Study Participants

Characteristic	Control group (n = 50)	Yoga group (n = 50)	p value
Age, years	52.2 $\pm$ 4.96	53.1 $\pm$ 5.9	0.47

Sex, male/female, %	50 male; 50 female	45 male; 55 female	0.548
Duration of T2DM, years	6.0 ± 1.85	5.5 ± 1.42	0.20
Fasting blood sugar, mg/dL	149.88 ± 23.15	151.91 ± 20.10	0.70
HbA1c, %	7.14 ± 1.03	6.83 ± 0.89	0.177
Fasting Insulin, µIU/mL	21.35 ± 2.52	23.58 ± 2.41	0.001
HOMA-IR	7.05 ± 1.19	9.58 ± 1.40	< 0.001
hsCRP, nmol/L	39.23 ± 4.28	40.23 ± 6.23	0.49
IL-1β, pg/mL	28.12 ± 2.05	39.66 ± 2.02	< 0.001
IL-6, pg/mL	3.17 ± 0.27	6.44 ± 1.09	< 0.001
Current antidiabetic treatment	Oral hypoglycemic drugs	Oral hypoglycemic drugs	Not applicable

Values are presented as mean ± SD unless otherwise stated. Sex values are reproduced as percentages from the study record and should be verified against the original participant-level record before final submission. T2DM = type 2 diabetes mellitus; HOMA-IR = homeostatic model assessment of insulin resistance; hsCRP = high-sensitivity C-reactive protein; IL = interleukin.

Participant flow

A total of 100 patients with T2DM were included, with 50 in the medication-only control group and 50 in the medication-plus-yoga group. Baseline sociodemographic and clinical characteristics are presented in Table 1. Both groups were scheduled for biochemical assessment on days

0, 15, 30, and 45. Across the 45-day observation period, the yoga group showed statistically significant changes in FBS, HbA1c, insulin, HOMA-IR, hsCRP, IL-1β, and IL-6, with follow-up p-values below 0.01 for each variable. In contrast, the control group showed comparatively small changes, and none of the reported follow-up p-values were below 0.05. The serial measurements are presented in Table 2.

Table 2: Glycemic, Insulin-Resistance, and Inflammatory Measures at Baseline and Follow-up

Parameter	Group	Day 0	Day 15	Day 30	Day 45	Follow-up p-value
FBS (mg/dL)	Control	149.88 ± 23.15	148.88 ± 25.12	148.88 ± 20.15	147.88 ± 24.15	0.17
FBS (mg/dL)	Yoga/Test	151.91 ± 20.10	153.14 ± 26.95	145.09 ± 25.81	131.20 ± 23.18	<0.01
HbA1c (%)	Control	7.14 ± 1.03	7.12 ± 0.83	7.12 ± 1.63	7.13 ± 0.73	0.91
HbA1c (%)	Yoga/Test	6.83 ± 0.89	7.31 ± 1.39	7.29 ± 1.38	6.21 ± 0.80	<0.01
Insulin (µIU/mL)	Control	21.35 ± 2.52	17.51 ± 2.12	17.51 ± 2.16	16.51 ± 2.06	0.06
Insulin (µIU/mL)	Yoga/Test	23.58 ± 2.41	10.95 ± 2.26	9.49 ± 2.09	9.89 ± 1.82	<0.01
HOMA-IR	Control	7.05 ± 1.19	6.05 ± 0.92	6.05 ± 1.02	5.85 ± 0.96	0.37
HOMA-IR	Yoga/Test	9.58 ± 1.40	3.98 ± 1.45	3.25 ± 1.71	3.09 ± 0.67	<0.01
hsCRP (nmol/L)	Control	39.23 ± 4.28	38.39 ± 6.59	38.96 ± 5.23	39.42 ± 5.48	0.86
hsCRP (nmol/L)	Yoga/Test	40.23 ± 6.23	31.49 ± 3.41	21.91 ± 5.40	18.3 ± 2.99	<0.01
IL-1β (pg/mL)	Control	28.12 ± 2.05	27.25 ± 4.12	27.14 ± 3.71	26.76 ± 2.75	0.43
IL-1β (pg/mL)	Yoga/Test	39.66 ± 2.02	30.77 ± 3.25	32.86 ± 4.17	25.14 ± 2.48	<0.01

IL-6 (pg/mL)	Control	3.17 ± 0.27	2.98 ± 0.32	3.71 ± 0.21	3.62 ± 0.12	0.91
IL-6 (pg/mL)	Yoga/Test	6.44 ± 1.09	5.76 ± 1.10	3.47 ± 1.40	3.35 ± 1.49	<0.01

Values are mean ± SD. FBS = fasting blood sugar; HOMA-IR = homeostatic model assessment of insulin resistance; hsCRP = high-sensitivity C-reactive protein.

By day 45, mean FBS in the yoga group had fallen to 131.20 ± 23.18 mg/dL and HbA1c to $6.21 \pm 0.80\%$. Insulin decreased to 9.89 ± 1.82 μ IU/mL, accompanied by a decline in HOMA-IR to 3.09 ± 0.67 . The inflammatory markers followed a similar overall pattern, with hsCRP decreasing to 18.3 ± 2.99 , IL-1 β to 25.14 ± 2.48 pg/mL, and IL-6 to 3.35 ± 1.49 pg/mL.

Correlation analysis showed that HOMA-IR was strongly associated with insulin across all three follow-up intervals. Significant correlations were also observed with IL-1 β throughout follow-up. The association with IL-6 was significant during the 0-15-day and 30-45-day intervals. hsCRP correlated inversely with HOMA-IR during the first interval but did not show significant correlations during the later intervals (Table 3).

Table 3: Correlation of HOMA-IR with Glycemic and Inflammatory Variables

Interval	Statistic	FBS	Insulin	hsCRP	IL-1 β	IL-6
0-15 days	R	0.82	0.99	-0.49	0.42	0.75
0-15 days	P	<0.01*	<0.01*	<0.01*	<0.01*	<0.01*
15-30 days	R	0.27	0.96	-0.20	0.63	0.22
15-30 days	P	0.11	<0.01*	0.25	<0.01*	0.21
30-45 days	R	0.38	0.95	0.07	0.75	0.83
30-45 days	P	0.03*	<0.01*	0.69	<0.01*	<0.01*

*Note. *Statistically significant correlation at $p < 0.05$*

Discussion

The present findings suggest that supervised yoga, when practiced alongside routine antidiabetic treatment, was associated with favorable changes in several metabolic and inflammatory parameters over the 45-day study period. Participants in the yoga group showed progressive reductions in fasting blood glucose, HbA1c, circulating insulin, and HOMA-IR, whereas the corresponding values in the control group remained relatively stable. The direction of these changes is broadly consistent with earlier studies in which regular yoga practice was associated with improved fasting glucose, glycated hemoglobin, insulin levels, and overall well-being among individuals with diabetes [6,8-10]. These findings support the possibility that yoga may complement conventional treatment by addressing both physical inactivity and stress-related influences on glucose metabolism.

The improvement in fasting glucose is particularly relevant because fasting hyperglycemia reflects abnormalities in hepatic glucose output as well as impaired peripheral insulin action. Regular yoga practice incorporates sustained muscular activity, stretching, controlled breathing, and relaxation, all of which may contribute to improved glucose utilization and metabolic regulation. The decline observed in HbA1c also suggests an overall improvement in glycemic

status. However, HbA1c represents average glycemic exposure over several weeks to months; therefore, changes detected during a 45-day intervention should be interpreted with appropriate caution. The reduction nevertheless followed the same overall direction as the changes in fasting glucose and insulin resistance.

The decrease in fasting insulin and HOMA-IR is an important observation because insulin resistance is a central metabolic abnormality in T2DM. A fall in HOMA-IR over the study period may indicate improved insulin sensitivity or a reduction in the amount of circulating insulin required to maintain glucose homeostasis. The strong positive association observed between fasting insulin and HOMA-IR at the different follow-up intervals is biologically expected because fasting insulin is itself a component of the HOMA-IR calculation. These findings should therefore be viewed primarily as supportive evidence of changing insulin resistance rather than as independent confirmation of a separate biological relationship.

An important consideration is that baseline HOMA-IR values were higher in the yoga group than in the control group. This imbalance may have influenced the apparent magnitude of improvement during follow-up, because participants starting with higher values have greater scope for reduction. Regression toward the mean may also partly

contribute to larger changes in participants with initially elevated measurements. The findings are therefore more appropriately interpreted in terms of changes over time and differences in the pattern of response between groups rather than relying only on absolute post-intervention values.

The inflammatory findings provide an additional perspective on the possible effects of yoga in T2DM. High-sensitivity C-reactive protein decreased considerably among participants practicing yoga, whereas little change was observed in the control group. hsCRP is widely used as a marker of low-grade systemic inflammation and has been associated with the development of T2DM and increased cardiometabolic risk [11]. A reduction in hsCRP during the intervention may therefore indicate attenuation of the chronic inflammatory state that frequently accompanies insulin resistance and diabetes.

Similar trends were noted for IL-1 β and IL-6. Both cytokines decreased progressively during the yoga intervention. IL-1 β has particular relevance to the pathophysiology of diabetes because prolonged exposure of pancreatic β -cells to elevated glucose concentrations can activate inflammatory pathways and promote IL-1 β -mediated β -cell dysfunction [12]. Persistent activation of these pathways may contribute to deterioration of insulin secretion and worsening glycemic control. The observed reduction in IL-1 β is therefore of interest, although the present study cannot establish whether the decrease directly influenced β -cell function.

IL-6 is another important inflammatory mediator linked with obesity, insulin resistance, and metabolic dysfunction. Its biological effects are complex and may differ according to the tissue of origin and duration of exposure. Nevertheless, persistently elevated circulating IL-6 is commonly associated with chronic low-grade inflammation in metabolic disease. Previous yoga-based interventions and systematic reviews have reported reductions in circulating inflammatory cytokines and C-reactive protein following regular practice [13-15]. The present observations are in agreement with this broader body of evidence and suggest that the benefits of yoga may extend beyond changes in glucose indices alone.

The correlation analysis further indicated that insulin resistance and inflammatory markers tended to change in parallel. IL-1 β showed a significant association with HOMA-IR across the reported follow-up intervals, while IL-6 was significantly associated with HOMA-IR during two of the three intervals examined. These associations are biologically plausible because inflammatory signaling and insulin resistance are closely interconnected in T2DM. Chronic inflammatory activity can interfere with insulin signaling, while hyperglycemia and excess metabolic stress

can, in turn, promote inflammatory responses. However, correlation does not establish a causal relationship, and the present results should not be interpreted as evidence that reductions in IL-1 β or IL-6 directly produced the observed improvement in insulin resistance.

Several mechanisms could potentially explain the observed metabolic and inflammatory changes. The physical component of yoga may enhance peripheral glucose uptake and improve insulin action, while breathing and relaxation practices may reduce sympathetic activity and stress-related neuroendocrine responses. A reduction in physiological stress could lower the influence of counter-regulatory hormones that adversely affect glucose metabolism. Regular participation in a structured yoga program may also encourage greater health awareness and adherence to lifestyle recommendations. The present study did not specifically measure autonomic function, cortisol, body-composition changes, dietary intake, or energy expenditure, and these mechanisms therefore remain possible explanations rather than demonstrated pathways.

Another point requiring consideration is that the intervention lasted only 45 days. This duration was sufficient to demonstrate short-term changes in fasting glucose, insulin resistance, and inflammatory markers, but longer follow-up would be necessary to determine whether these improvements are sustained. In addition, the participants continued their prescribed antidiabetic medication throughout the study. The observed changes should therefore be regarded as the effect of yoga added to usual treatment and not as evidence that yoga can replace pharmacological therapy.

Taken together, the findings suggest that a structured yoga program may be a useful adjunct to conventional management of T2DM. Daily practice combining physical postures, controlled breathing, relaxation, and meditation was associated with improvement in glycemic measures, insulin resistance, and selected inflammatory biomarkers over the study period. The simultaneous decline in metabolic and inflammatory indices is encouraging, but the findings should be interpreted in the context of baseline differences between the groups and the relatively short duration of follow-up. Larger studies with longer observation periods, more balanced baseline characteristics, and adjustment for potential confounding variables would help clarify the extent and durability of these effects.

Generalizability: The findings are most applicable to medically stable adults with T2DM who are able to participate in a supervised daily yoga program and attend repeated biochemical follow-up. Generalization to patients with major comorbidities, advanced diabetic complications,

different medication regimens, or unsupervised community-based yoga practice should be made cautiously.

Conclusion

A 45-day structured yoga program, practiced in addition to routine antidiabetic treatment, was associated with improvement in fasting glucose, HbA1c, insulin levels, HOMA-IR, hsCRP, IL-1 β , and IL-6 among patients with T2DM. The combined changes in glycemic and inflammatory markers suggest that yoga may offer additional benefit as a supportive component of diabetes management. However, these findings should be confirmed through larger, well-controlled studies with longer follow-up, better baseline matching, and careful adjustment for medication use and other potential confounding factors.

Limitations

The study had a short 45-day follow-up. Group allocation was non-randomized and based on participation in the yoga program; therefore, selection bias, residual confounding, and regression toward the mean cannot be excluded. Allocation concealment and blinding were not described. Some baseline biochemical values differed between groups, and adjusted analyses were not reported.

Recommendations

Yoga may be incorporated as an adjunct to routine medical management for patients with T2DM who can participate safely. Future studies should use longer follow-up, clearly defined allocation methods, standardized reporting of medication and lifestyle factors, and appropriate adjustment for baseline group differences. Integrating dietary assessment and other lifestyle measures would help clarify the independent contribution of yoga. Molecular studies examining insulin-signaling pathways may also help explain the biological basis of the observed changes.

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Abbreviations

ELISA: Enzyme-linked immunosorbent assay

FBS: Fasting blood sugar

HbA1c: Glycated hemoglobin

HOMA-IR: Homeostatic model assessment of insulin resistance

hsCRP: High-sensitivity C-reactive protein

IL-1 β : Interleukin-1 beta

IL-6: Interleukin-6

T2DM: Type 2 diabetes mellitus

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Conflict of interest

The authors declared no potential conflict of interest relevant to this study.

Author contributions

VKK contributed to the conception and design of the study, development of the methodology, supervision of the research work, interpretation of the findings, and preparation of the manuscript. SPN contributed to laboratory investigations, data organization, statistical analysis, literature review, interpretation of the biochemical findings, and drafting of the manuscript. JRN contributed to the yoga sessions, interpretation of the yoga and behavioral components of the study, literature review, discussion of the findings, and critical revision of the manuscript. All authors reviewed the manuscript and approved the final version for submission.

Data availability

Data available on request

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