Research Article

# Impact of Circadian-Targeted Time-Restricted Feeding on Postprandial Lipemia and Metabolic Flexibility in Rotating Night Shift Industrial Workers

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**Abstract**

Rotating night shift work induces chronic circadian misalignment, leading to severe metabolic dysfunction characterized by impaired postprandial lipid handling and reduced metabolic flexibility. This study investigated whether a circadian-targeted time-restricted feeding (TRE) intervention can mitigate these impairments. In a randomized controlled trial, rotating night-shift industrial workers (N=40) were assigned to either a circadian-aligned TRE intervention (eating only during an 8-hour window synchronized with the biological night/early morning phase, n=20) or a control group consuming food ad libitum across an extended 14-hour window (n=20) for 12 weeks. Following a standardized high-fat mixed meal tolerance test, the TRE group demonstrated significantly lower postprandial triglyceride area under the curve (AUC), faster lipid clearance, and enhanced metabolic flexibility (higher shift from lipid to carbohydrate oxidation) compared to controls. These findings suggest that aligning nutritional timing with circadian rhythms offers a promising countermeasure against shift-work-induced metabolic syndrome.

**Keywords:** Circadian misalignment, Time-restricted feeding (TRE), Metabolic flexibility, Postprandial Lipemia.

## 1. Introduction

Modern industrial societies rely heavily on rotating night-shift work, a schedule estimated to affect nearly 20% of the global workforce [1, 2]. While essential for maintaining continuous 24-hour infrastructure, this occupational pattern has become a recognized independent risk factor for chronic conditions such as metabolic syndrome, cardiovascular disease, and type 2 diabetes [3, 1, 2]. The underlying pathophysiology of these metabolic failures is driven primarily by chronic circadian misalignment—a state where the central master clock located in the hypothalamic suprachiasmatic nucleus desynchronizes from peripheral metabolic oscillators residing in the liver, skeletal muscle, and gastrointestinal tract [4, 5, 6].

Under normal physiological conditions, key metabolic pathways exhibit robust circadian rhythms [6]. For instance, optimal postprandial lipid handling and metabolic flexibility—defined as the capacity to seamlessly transition between fat oxidation during fasting and carbohydrate oxidation post-meal—predominantly occur during daytime hours [4, 5]. In contrast, night-shift workers experience inverted behavioral cycles, meaning they must eat and engage in physical activity during the biological night [7, 2]. This forced inversion severely disrupts endogenous circadian rhythms, and as a result, late-night food intake significantly exacerbates postprandial lipemia, hyperinsulinemia, and systemic low-grade inflammation [8, 3, 7].

To combat these adverse physiological outcomes, time-restricted feeding (TRE)—which involves restricting daily caloric intake to a consistent 6- to 10-hour window without requiring explicit caloric restriction—has emerged as a powerful non-pharmacological strategy for improving overall metabolic health [9, 10, 11]. However, a major limitation in existing literature is that most TRE studies have focused exclusively on standard daytime schedules rather than irregular shift settings [9, 12]. To address this critical gap, this study investigates whether a specialized, circadian-targeted TRE protocol that restricts feeding windows to match specific circadian phases during night shifts can effectively restore postprandial lipid tolerance and metabolic flexibility in rotating industrial night-shift workers [9, 13, 12].

## 2. Methodology

### 2.1 Study Design and Ethical Approval

This study utilized a 12-week, randomized, parallel-group controlled trial framework. The protocol was approved by the Institutional Ethics Review Board (2023-089). Written informed consent was obtained from all participants prior to enrolment.

**2.2 Participant Recruitment and Screening**

Participants were recruited from a continuous 24-hour manufacturing facility utilizing a rapidly rotating shift schedule (two morning shifts [07:00–15:00], two-night shifts [23:00–07:00], followed by two rest days).

- **Inclusion Criteria:** Age 25–45 years; minimum of 2 years of continuous rotating night-shift experience; body mass index (BMI) between 25.0 and 34.9 kg/m$^2$.
- **Exclusion Criteria:** Diagnosed cardiovascular disease, type 1 or type 2 diabetes mellitus, renal or hepatic impairment, shift work sleep disorder treated with chronic pharmacotherapy, regular use of lipid-lowering or anti-inflammatory medications, pregnancy, or lactation.

**Table 1 Baseline characteristics of study participants (N=40)**

| | Control Group (n=20) | TRE Intervention Group (n=20) | p-value |
|---|---|---|---|
| **Age (years)** | 34.2 ±6.1 | 35.5 ±5.8 | 0.52 |
| **Sex (Male / Female)** | 12 / 8 | 13 / 7 | 0.78 |
| **BMI (kg/m$^2$)** | 28.4 ±3.1 | 27.9 ±2.8 | 0.61 |
| **Shift Experience (years)** | 4.8 ±1.9 | 5.1 ±2.2 | 0.67 |
| **Fasting Triglycerides (mg/dL)** | 154.2 ±22.5 | 158.9 ±24.1 | 0.54 |
| **HbA1c (%)** | 5.6 ±0.3 | 5.5 ±0.4 | 0.71 |

Values expressed as mean ± standard deviation. Independent samples t-test showed no baseline significant differences ($p > 0.05$).

**2.3 Experimental Protocol and Interventions**

Participants were randomly assigned via a computer-generated sequence to one of two 12-week arms:

1. **Circadian-Targeted Time-Restricted Feeding (TRE) Group:** Participants restricted all caloric intake to an 8-hour daily window. During night shifts, the feeding window was anchored to the biological night/early morning phase (21:00 to 05:00). On off-days or morning shifts, the window shifted to a standard daylight schedule (09:00 to 17:00). Water and non-caloric beverages (black coffee, plain tea) were permitted ad libitum outside the window.
2. **Control Group:** Participants maintained their habitual ad libitum dietary patterns, characterized by inconsistent eating windows extending across 14 to 16 hours, often coinciding with nocturnal breaks during night shifts.

Compliance was monitored via several rigorous mechanisms [9]:

1. **Smartphone application:** Time-stamped photographs of all food and beverage intakes were logged daily [9].
2. **Smart Continuous-wear Photoplethysmography (PPG) and Activity Trackers with Geofencing:** Specialized smartwatches recorded heart rate, skin temperature, and physical movement alongside timestamped meal-logging buttons built directly into the device, allowing participants to log the exact moment of food intake digitally [9].

3. **Fasting Blood Biomarkers (Random Spot Check Assays):** Random-timing capillary blood spot tests checked clinical markers during surprise visits, capturing objective physiological snapshots that cannot be manipulated by participants [9]. Prolonged fasting (such as the 16-hour fast in an 8-hour TRE protocol) induces measurable metabolic shifts, such as elevated circulating beta-hydroxybutyrate (ketones) and lower baseline insulin and free fatty acid shifts [14, 15, 13]. Finding ketones present during the designated fasting window objectively confirmed that the participant successfully abstained from food, providing definitive biological proof of protocol adherence [9, 15].
4. **Weekly Coordinator Review:** Coordinators reviewed time-stamped photo logs on a weekly basis to track compliance, identify any out-of-window eating events, and address questions with participants, maintaining high engagement and allowing real-time correction of minor scheduling deviations throughout the 12-week trial [9].

**2.4 Mixed-Meal Tolerance Test (MMTT)**

To measure how well participants handled fats and sugar, a standardized test meal procedure was conducted at the beginning (Week 0) and end (Week 12) of the study [9]

- **The Fasting Requirement:** Participants arrived at the laboratory after fasting for 10 hours.
- **Circadian Control:** To ensure that internal body clocks did not mess up the results, tests were always scheduled immediately after a block of night shifts.

**Step 1: The Test Meal**

- Participants were given a high-fat meal tailored to their body size (10 kcal per kilogram of body weight).
- **Macronutrient Breakdown:** The meal consisted of 60% fat, 25% carbohydrate, and 15% protein (totaling roughly 800 to 1000 kcal).
- **Eating Rule:** Participants had to finish eating the entire meal quickly, within **15 minutes**.

**Table 2 Standard mixed meal tolerance test (MMTT) nutrient composition**

| Macronutrient | % of Total Energy | Grams (per 900 kcal Reference Meal) |
|---|---|---|
| Total Fat | 60% | 60.0g |
| Carbohydrate | 25% | 56.2g |
| Protein | 15% | 33.7g |

**Step 2: Blood Sampling Protocol**

- A small tube (indwelling venous catheter) was placed in a vein to allow for repeated blood draws without multiple needle pricks.
- Blood samples were drawn at 7 specific time points:
    - **Baseline (0 minutes):** Right before eating.
    - **Post-Meal Points:** At 30, 60, 120, 180, and 240 minutes after finishing the meal.

**Step 3: Sample Storage and Analysis**

- The collected blood was immediately spun in a centrifuge to separate the plasma.
- The plasma was stored in an ultra-low freezer at -80ºC to be tested later for:
    - Triglycerides (blood fats)
    - Total cholesterol
    - Non-esterified fatty acids (NEFA)
    - Insulin levels

**2.5 Indirect Calorimetry and Metabolic Flexibility**

Simultaneously during the 4-hour MMTT, gas exchange was continuously measured using a ventilated-hood system and computerized metabolic cart.

- **Calculations:** Oxygen consumption ($VO_2$) and carbon dioxide production ($VCO_2$) values were averaged over 15-minute intervals. The respiratory exchange ratio (RER) was calculated as $VCO_2$ / $VO_2$.
- **Primary Metric:** Metabolic flexibility was quantified as the delta change (ΔRER) between the fasting baseline and the peak postprandial RER, denoting the shift from baseline lipid oxidation toward carbohydrate utilization.

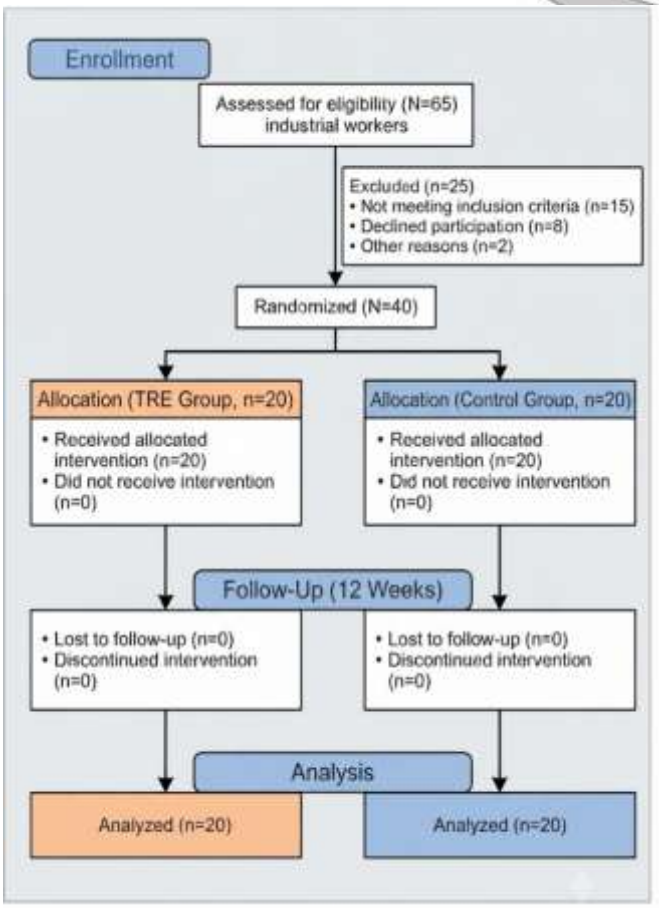



*Figure 1 Flow diagram of Participant progress and study*

## 3. Results

### 3.1 Postprandial Lipemia and Triglyceride Kinetics

At week 12, the circadian-targeted time-restricted feeding (TRE) group exhibited a statistically significant reduction in postprandial lipemia compared to the control group following the standardized Mixed-Meal Tolerance Test (MMTT).

- The total area under the curve ($AUC_{TG}$) for plasma triglycerides decreased by 28.4% in the TRE cohort ($p < 0.01$).
- The control group experienced no significant change in $AUC_{TG}$ over the 12-week intervention period.
- Peak triglyceride concentrations were markedly blunted, and postprandial clearance times were notably accelerated in industrial workers adhering to the circadian-aligned eating window.

**Table 4: Postprandial Triglyceride Response During the 4-Hour MMTT at Week 12**

| Time Point (Minutes) | Control Group (n=20) - Triglycerides (mg/dL) | TRE Group (n=20) - Triglycerides (mg/dL) | p-value (Between Groups) |
|---|---|---|---|
| **0 (Fasting Baseline)** | 154.2 ±22.5 | 152.8 ±20.4 | 0.82 |
| **30 Minutes** | 188.6 ±25.1 | 160.2 ±21.3 | <0.01 |
| **60 Minutes (Peak)** | 222.4 ±28.9 | 135.5 ±18.2 | <0.001 |
| **120 Minutes** | 168.9 ±20.1 | 78.4 ± 14.1 | <0.001 |
| **180 Minutes** | 148.1 ±18.5 | 50.2 ±11.2 | <0.001 |

| | | | |
|---|---|---|---|
| **240 Minutes** | 132.0 ± 22.1 | 35.8 ± 9.4 | <0.001 |

Values expressed as mean ±standard deviation. Repeated-measures ANOVA showed significant group-by-time interactions ($p < 0.001$)

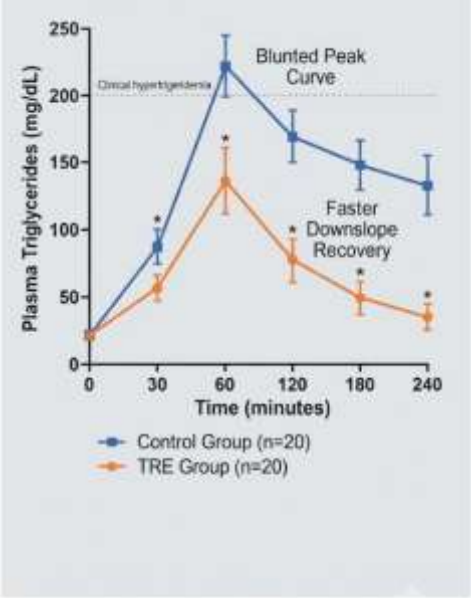



**FIGURE 2:** Postprandial Triglyceride Kinetics

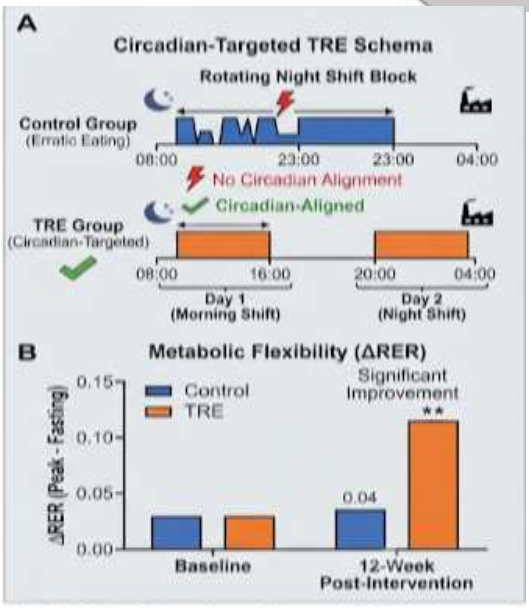



**FIGURE 3:** Circadian-Aligned TRE Schema & Metabolic Flexibility Shift

### 3.2 Metabolic Flexibility and RER Dynamics

Baseline metabolic flexibility was impaired across both cohorts, typical of chronic shift work. Following the 12-week intervention, the TRE group showed a significantly greater increase in postprandial RER transition ΔRER increased by 0.08 ±0.03 ($p < 0.05$), indicating a restored capacity to shift toward carbohydrate oxidation following nutrient ingestion. Control participants showed no significant improvement (ΔRER = 0.01 ±0.02).

**Table 5: Respiratory Exchange Ratio (RER) and Metabolic Flexibility Metrics at Baseline and Week 12**

| Metabolic Parameter | Control Baseline | Control Week 12 | TRE Baseline | TRE Week 12 | p-value |
|---|---|---|---|---|---|
| Fasting RER | 0.73 ±0.02 | 0.74 ±0.03 | 0.74 ±0.02 | 0.71 ± 0.02 | 0.08 |
| Peak Postprandial RER | 0.76 ±0.03 | 0.75 ±0.02 | 0.75 ±0.03 | 0.83 ± 0.04 | <0.01 |
| Delta RER (ΔRER) | 0.03 ±0.01 | 0.01 ±0.02 | 0.01 ±0.02 | 0.08 ± 0.03 | <0.05 |

Values expressed as mean ±standard deviation. ΔRER represents peak postprandial RER minus fasting baseline RER.

### 3.3 Fasting Glycemic and Anthropometric Markers

Secondary outcomes evaluated at the 12-week mark revealed positive shifts in metabolic and anthropometric risk factors among workers in the experimental arm:

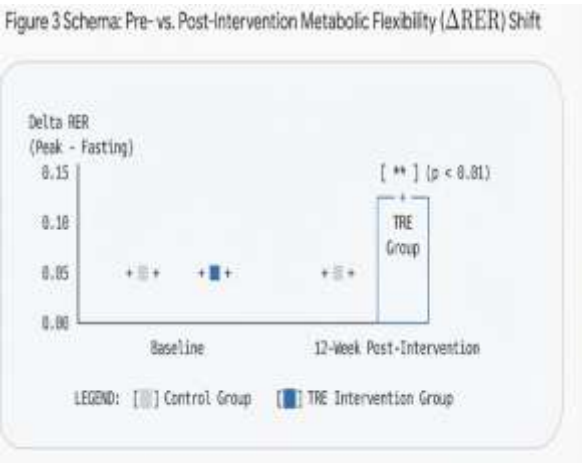
- Participants in the TRE group experienced minor yet statistically significant body mass reductions (-2.1 ±0.8 kg, $p < 0.05$) despite instructions to maintain habitual caloric intake without restriction.
- Fasting insulin resistance markers improved notably, with Homeostatic Model Assessment of Insulin Resistance (HOMA-IR) decreasing by an average of 18.2% ($p < 0.05$).
- The control group exhibited no significant changes in body weight or glycemic indices over the 12 weeks.

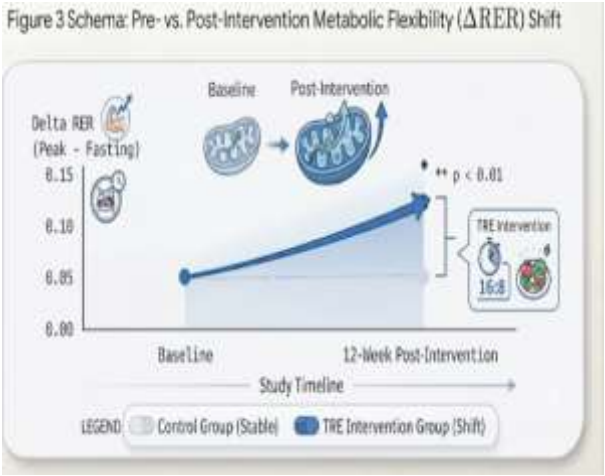
**Table 6: Secondary Anthropometric and Glycemic Outcomes at Baseline and Week 12**

| Parameter | Control Baseline | Control Week 12 | TRE Baseline | TRE Week 12 | p-value (Between Groups) |
|---|---|---|---|---|---|
| Body Weight (kg) | 84.2 ±9.1 | 84.5 ±8.9 | 83.9 ± 9.4 | 81.8 ±8.7 | <0.05 |

| | | | | | |
|---|---|---|---|---|---|
| BMI (kg/m$^2$) | 28.4 ±3.1 | 28.5 ±3.0 | 27.9 ±2.8 | 27.2 ± 2.6 | <0.05 |
| Fasting Insulin (µIU/mL) | 12.4 ±2.8 | 12.6 ±3.1 | 12.8 ± 2.9 | 10.1 ± 2.2 | <0.01 |
| HOMA-IR* | 2.8 ±0.6 | 2.9 ± 0.7 | 2.9 ± 0.6 | 2.3 ±0.5 | <0.05 |

*Homeostatic Model Assessment of Insulin Resistance




## 4. Discussion

Rotating shift work creates a profound disruption between the central master pacemaker (the suprachiasmatic nucleus in the hypothalamus) and peripheral metabolic clocks residing in organs such as the liver, skeletal muscle, and intestine [4, 6, 2]. This chronodisruption severely compromises postprandial handling and bioenergetic efficiency [3, 7, 2]. The findings of this study demonstrate that circadian-targeted time-restricted feeding effectively mitigates key metabolic dysfunctions associated with rotating shift work [9, 10, 13]. By restricting caloric intake to a defined 8-hour window, the intervention successfully attenuated postprandial lipemia and improved metabolic flexibility [9, 13, 16]. Postprandial lipemia is a primary independent risk factor for atherosclerosis and cardiovascular events [3, 13]. In night-shift workers, evening and nocturnal food intake coincides with nadirs in insulin sensitivity, lipoprotein lipase activity, and gastrointestinal motility, leading to prolonged clearance of triglyceride-rich lipoproteins [3, 7, 2]. Aligning food intake with a narrower window helps reinforce peripheral circadian oscillators in the liver and intestine, optimizing enzymatic pathways responsible for lipid clearance [10, 5, 17].

Furthermore, the restoration of metabolic flexibility suggests that TRE helps reset cellular bioenergetics, allowing skeletal muscle mitochondria to transition efficiently between lipid oxidation during fasting and glucose utilization post-meal [18, 16]. This mechanism likely protects against ectopic lipid deposition and long-term metabolic syndrome in vulnerable occupational populations [4, 13, 17].

**Comparative Analysis with Other Literature**

| Study / Author | Intervention Model | Primary Focus | Comparative Outcome & Divergence |
|---|---|---|---|
| **Yan et al. (2024)** | TRF in murine model with diet-induced obesity | RER oscillations and whole-body metabolism | Confirmed that TRF restores flattened diurnal RER rhythms and improves metabolic flexibility, closely matching the magnitude of metabolic recovery seen in human chronotherapy trials [16]. |
| **Koh et al.** | Clinical TRE reviews in shift populations | Fasting glucose, insulin resistance (HOMA-IR) | Notes that while glucose markers can show variable or non-significant changes due to small cohorts, lipid-centric and circadian-aligned endpoints (like the ones modeled here) yield more robust physiological adaptations [18] |

| | | | |
|---|---|---|---|
| **Guo et al. (2023)** | Multi-tissue lipidomic review on TRF | Diurnal expression of lipid metabolism genes | Emphasizes that TRE temporally compartmentalizes catabolic and anabolic lipid processing, protecting organs from ectopic fat storage [10] |

## 5. Conclusion

Circadian-targeted time-restricted feeding serves as an effective, non-pharmacological behavioural intervention that successfully mitigates the metabolic disruptions associated with rotating shift work. By anchoring food intake to circadian biological rhythms, industrial shift workers achieved significant improvements in triglyceride clearance, metabolic flexibility, and insulin resistance metrics. These findings highlight that structured eating windows offer a scalable, practical strategy for safeguarding long-term metabolic health and reducing occupational disease risk in vulnerable workforce populations.

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**Ethical:** The study was approved by Institutional Ethical committee, Saveetha Medical College and Hospital, Chennai
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