Time-restricted eating: Integrating the what with the when

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Abbreviations

ADF   Alternate day fasting
ALT   Alanine transaminase
ASA24 Automated Self-Administered 24-hour dietary assessment tool
AST   Aspartate aminotransferase
AUC   Area under the curve
BMI   Body mass index
BP    Blood pressure

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CER  Continuous energy restriction
CGM  Continuous glucose monitor
CHO  Carbohydrate
CMT  Consistent meal timing
dTRE Delayed time restricted eating
EI   Energy intake
eTRE Early time restricted eating
FBG  Fasting blood glucose
FDDNS Food and Nutrient Database for Dietary Studies
HbA1c Glycated haemoglobin
HDL  High density lipoprotein
HEI  Healthy eating index
HRQoL Health-related quality of life
IF   Intermittent fasting
MBD  Macronutrient based diet
MCC  MyCircadianClock
MetS Metabolic syndrome
NAFLD Non-alcoholic fatty liver disease
OGTT Oral glucose tolerance test
SCN  Superchiasmatic nucleus
SDA  Standard dietary advice
TAG  Triglycerides
TRE  Time-restricted eating
TRF  Time-restricted feeding
T2D  Type 2 diabetes
Abstract

Time-restricted eating (TRE) is a popular dietary strategy that emphasises the *timing* of meals in alignment with diurnal circadian rhythms, permitting *ad libitum* energy intake during a restricted (~8-10 h) eating window each day. Unlike energy-restricted diets or intermittent fasting interventions that focus on weight loss, many of the health-related benefits of TRE are independent of reductions in body weight. However, TRE research to date has largely ignored *what* food is consumed (i.e., macronutrient composition and energy density), overlooking a plethora of past epidemiological and interventional dietary research. To determine some of the potential mechanisms underpinning the benefits of TRE on metabolic health, future studies need to increase the rigour of dietary data collected, assessed, and reported to ensure a consistent and standardised approach in TRE research. This perspective provides an overview of studies investigating TRE interventions in humans and considers dietary intake (both *what* and *when* food is eaten) and their impact on selected health outcomes (i.e., weight loss, glycaemic control). Integrating existing dietary knowledge about *what* food is eaten with our recent understanding on *when* food should be consumed is essential to optimise the impact of dietary strategies aimed at improving metabolic health outcomes.

**Keywords:** diet, nutrition, timing, energy intake, fasting

**Statement of significance:** Time-restricted eating (TRE) is a dietary strategy that focuses on the *timing* of meals, but frequently neglects the quality and quantity of food consumed. This perspective challenges researchers in the field of TRE to incorporate rigorous dietary assessment to unravel the complex relationships between the *type* of food consumed and the *timing* of meals.
Introduction

Dietary advice for improving metabolic health in individuals with non-communicable diseases such as obesity and type 2 diabetes (T2D) has traditionally focussed on what food is consumed, with an emphasis on dietary quality and energy intake. Decades of research from nutrition scientists has provided robust evidence of the metabolic responses to diets of differing macronutrient profiles (i.e., Mediterranean, low-carbohydrate, high-fat, high-protein) as well reduced energy intakes (i.e., very low-energy diets). Recently, there has been growing recognition that the timing of meals is critical for metabolic health and well-being, and that manipulating the feeding–fasting cycle carries important consequences for a number of physiological and metabolic processes (1–5). Time-restricted eating (TRE), often called the 16:8 diet, is a popular dietary strategy placing emphasis on the timing of food but permits ad libitum energy intake during a restricted (~8-10 h) eating window each day. Several recent reviews have highlighted the potential for TRE to induce improvements to body weight (i.e., reduce obesity) and other cardiometabolic health markers (6–9). Many of the benefits of TRE on metabolic health are independent of weight loss, but instead are underpinned by the timing of meals in alignment with circadian rhythms. To date, many of the interventional studies of TRE have largely ignored what food is consumed and its quality and quantity (i.e., macronutrient composition and energy density), with a sole focus on when food is consumed. This perspective provides an overview of studies investigating TRE in humans highlighting both what and when food is consumed. Our intent is to incorporate the decades of dietary intake research of what is eaten (i.e., the premise of dietetics as a profession) into future TRE investigations. Integrating dietary composition and quality with timing is key to unravel the complex relationships between the types of foods consumed and the timing of meals to determine their unique roles underpinning improvements in metabolic health. Before
providing an analysis of the dietary components of TRE studies to date, we provide important working definitions and a brief background of the evolution of TRE interventions.

**Current dietary strategies for improving metabolic health**

The majority of evidence-based dietary interventions prescribed to improve metabolic health and/or weight loss can be broadly classified as either: 1) chronic energy restriction (CER), in which daily energy intake is reduced by up to 40%, but meal frequency and timing remain unchanged; 2) intermittent fasting (IF), where one day or several days of fasting are interspersed with normal *ad libitum* eating patterns, and meal frequency and timing remaining unchanged on the days of food intake (e.g., alternate day fasting (ADF) and the 5:2 diet); or 3) time-restricted eating (TRE), in which food is consumed *ad libitum* but the eating duration (i.e. the time between the first and last energy intake of the day) is typically reduced from a 12–16 h ‘eating window’ to <8-12 h (7) (**Figure 1**).

Importantly, we and others (10,11) regard TRE to be a distinct dietary intervention rather than a modified form of IF. Specifically, TRE interventions do not intend to reduce energy intake, in contrast with all IF regimes. Furthermore, CER and IF are not chrono-nutritive therapies *per se*, in that they do not restrict food consumption to specified times of day to play off chronobiology. Instead, their therapeutic value and any positive health outcomes are mainly derived from chronic or intermittent periods of energy restriction. TRE is a chrono-nutritional strategy offering a less food-focused approach, where the timing of meals is closely aligned with typical metabolite and hormonal profiles over 24-h periods, in an ~8-10 h eating window. A requirement for TRE to be considered a chrono-nutritional strategy is the alignment of meals with typical circadian oscillations of hormonal profiles, with insulin sensitivity declining during the day and cortisol and growth hormone peaking in the morning.
and evening, respectively (12,13). Indeed, the TRE literature to date suggests that later or self-selected TRE periods are less effective in improving markers of metabolic health (Figure 2). Where TRE interventions have induced energy restriction, it is likely that the alignment of energy intake with circadian patterns of hormones and metabolites is less important than for energy-matched TRE.

Studies of TRE to date have exploited several different approaches, with such variations, in part, underpinning inconsistencies in their success or failure to improve health outcomes (Figure 2). Many short-term (less than 3 months) TRE protocols have been associated with moderate energy restriction (14–19) resulting in weight loss and associated health benefits. Depending on the duration of the feeding-fasting cycle, TRE can inadvertently reduce energy intake and/or alter macronutrient intakes via reductions in discretionary “time-of-day” foods such as alcohol and confectionary, that are typically consumed in the evening (i.e., outside the ‘eating window’ of TRE protocols). TRE protocols that do not restrict energy intake but align the timing of meals and the eating window to cycles in hormone and metabolite oscillations, also elicit improvements in health outcomes. From the well-controlled (all food/meals provided), early and mid-TRE human studies, this is the case (20–23), but far less evidence is available from free-living interventions (24). Further work is needed to corroborate that circadian-aligned TRE intakes lead to beneficial outcomes irrespective of energy intake. Additionally, ‘what’ participants are consuming throughout the TRE period can have a significant impact on outcomes, yet for the most part dietary intake has been poorly reported in TRE studies.
**Time-restricted eating: From pre-clinical to human intervention studies**

The concept of TRE and its basis in chronobiology originates from pre-clinical studies of mice in which food availability was synchronised to the diurnal rhythms of a cluster of genes responsible for regulating 24-h circadian cycles and compared to energy-matched *ad libitum* food availability throughout the day. When food was only available during the animals waking hours (overnight) (25), or restricted to a shorter window (26), mice gained less weight and body fat, and displayed improved glucose tolerance and levels of inflammatory markers. These animal studies of time-restricted feeding (TRF) provide evidence that *ad libitum* food intake is associated with disrupted circadian rhythms and adverse health outcomes (25,26). Furthermore, when metabolically challenged with high-fat, high-sucrose diets during TRE, mice lost more body weight and improved circulating metabolites compared to ad libitum intake (i.e. no TRE) (26). The mechanism underlying the beneficial effect of TRF are complex and are likely to act on multiple pathways that impinge on the circadian clock and improve robustness of oscillation of clock components and downstream targets (4). An evaluation of the mechanistic bases of pre-clinical data conducted in rodents has been reviewed previously (27–29). The translation of pre-clinical TRF data has several limitations: the length of time spent fasting for most animal models varies substantially compared to humans, with the time of eating for mice/rodents generally confined to nocturnal hours. In contrast, humans consume the majority of daily energy during the day, with light being a major photopic signal to the body’s central pacemaker, the superchiasmatic nucleus (SCN), influencing circadian oscillations. In humans, the few energy-matched studies in which meal timing has been rigorously controlled confirm earlier observations in animal models, providing “proof of concept” that the timing of meals has profound consequences on
physiology, and can be employed as an intervention to treat or prevent obesity and other metabolic conditions.

The results of several well-controlled studies in humans (i.e., interventions where all meals were quantified and provided to participants) provide strong evidence that TRE is an efficacious intervention for improving metabolic health outcomes (20–23). In a proof-of-concept study using a cross-over design, Sutton et al. (20) reported that five weeks of isoenergetic early TRE (0800-1400 h, 3 meals of 33% EI with 50% from CHO) improved measures of insulin sensitivity, blood pressure, beta-cell responsiveness and markers of oxidative stress in men with prediabetes compared to when they consumed the same dietary intake over 12 h (0800- 2000 h). That study (20) provided the first evidence to suggest that some of the health benefits of TRE may be independent of energy intake and weight loss. These researchers also collected preliminary data on the feasibility and acceptability of early TRE, with participants reporting that the challenge of eating within a 6 h window was more difficult than the requirement to fast for 18 h each day (20). In another short-term intervention of early TRE (4 days, eating window of 0800-1400 h, 3 meals of 33% EI with 50% from CHO), isoenergetic TRE reduced 24 h glucose concentrations and glycaemic variability in individuals with prediabetes compared to a 12 h eating window (0800 – 2000 h) (21). Similarly, reduced nocturnal glucose concentrations are observed after only five days of isoenergetic TRE (1000-1800 h, 3 meals of 25:35:40% EI with 30% from CHO) in men with obesity (23). The mechanisms by which early- and mid-TRE protocols induce beneficial outcomes in the absence of energy restriction is likely related to a combination of improved circadian glucose homeostasis, reduced oxidative stress, improved beta-cell function, increased autophagic flux and increased ketone body production (30). From the evidence to date, both the start and finish time and the duration of the eating window are important
considerations for translation to practice in maximizing health outcomes from TRE interventions.

In contrast to the robust-laboratory controlled TRE studies, many of the human studies of TRE conducted in free-living conditions have simultaneously manipulated both the time of day and the duration of the eating window, making it difficult to determine which of these perturbations to normal eating habits is responsible for any changes in health outcomes (20–23,31). Based on the results of studies where energy intake has been estimated (14–17,32), the notion that a shortened eating window might lead to a reduction in daily energy intake has gained credibility. However, the majority of free-living TRE interventions have neither quantified or estimated energy intake, and have not consistently reported improved health outcomes after TRE protocols (18,24,33–39). Most studies that fail to report the dietary intake of their participants are either late or delayed TRE (e.g., first eating occasion after 1200 h) or have required participants self-select their individual eating windows, with the caveat that there have been more late-TRE and self-selected TRE studies conducted to date. Further, many studies investigating TRE omit, or conduct only limited dietary analysis (i.e., baseline and end of intervention only).

The lack of dietary information reported in many studies is, in part, due to a focus on TRE interventions being about the timing of food intake, and not the types or amounts of food consumed. However, the lack of detailed dietary intake assessments and reported data makes it unclear whether the health benefits from TRE are derived from changing the timing of food intake, reducing the energy content of food consumed, altering the types of foods consumed (i.e., macronutrient composition) or a combined effect. Of course, changing both the timing and amount/types of food consumed may have synergistic or additive effects and further
work will be required to tease out potential mechanisms responsible for some of the improved metabolic health outcomes observed after TRE protocols.

**Improving the quality of dietary assessment in future time-restricted eating interventions**

The current literature of human interventions of TRE is limited and impacted by a lack of reliable and comprehensive dietary analysis. To present the dietary analysis of TRE studies to date, we conducted a literature search using PubMed, Google Scholar and cross-checking of citations of other research studies to summarise human TRE studies (Table 1). We divided investigations into early-TRE (eating window finishing by 1700 h), mid-TRE (delayed first eating occasion and eating window finishing by 1900 h) and late-TRE (TRE beginning from 1200 h), as well as those which had self-selected (i.e., unspecified) TRE eating windows. Of the 26 free-living TRE interventions summarised in Table 1, more than one-third had no analysis of either dietary intake or dietary quality. Most studies that report reductions in body weight had a concomitant decrease in total energy intake (14,16,40,41), but many provided little or no dietary analysis (18,35,37–39). One might assume that participants undertaking TRE protocols that did not induce a reduction in body weight and/or changes in body composition, and neglected to conduct any analysis of dietary intake, failed to change their dietary intake (quality or quantity) (33,34,36). However, the interventions that have provided meals matched for energy intake, and in which only the timing of eating is altered, demonstrate that a reduced energy intake may not be necessary for improvements to a selected metabolic health outcomes (20–23). Whether standard dietary advice regarding food quality induces additive and superior health outcomes to appropriately timed TRE has yet to be investigated (i.e., improving both what and when individuals consume food). To reach consensus between TRE interventions, traditional dietary records for a minimum of three
days (two weekdays and one weekend day), undertaken at least three times (baseline, mid-
point, and end of intervention) for the determination of energy and macronutrients should be
a minimum requirement, and provide valuable information regarding the most effective
protocol of TRE. While frequent (i.e. daily), comprehensive and extended dietary analysis
(i.e., macronutrients, micronutrients, dietary patterns, core food group analysis, level of
processed food and timing of all meals/snacks) throughout a TRE intervention would provide
valuable information, it is important to be mindful of the dietary analysis skills of research
teams, the time burden to participants of daily records along with the impact that dietary
recording has on dietary intake (42).

The other, less studied yet important dietary component is the change of macronutrient and
energy distribution across meals, as well as number of meals and snacks consumed during a
day. Typically, in Western cultures/societies, breakfast is the most carbohydrate-centric meal
yet contributes the least to total daily energy intake. In the evening, dinner is generally higher
in protein compared to other meals, as well as being the largest meal with regard to total
energy intake. Due to lack of detailed dietary data reported in previous TRE interventions, it
is currently unknown if TRE protocols change the distribution or intake of macronutrients at
meals across the day.

In addition to failing to report energy intake, most studies of TRE that have manipulated the
size of meals throughout the day do not specify what proportions of macronutrient have been
provided/consumed at each meal. The TRE studies that have utilised meal photo timing have
provided a comprehensive analysis of the number of eating occasions (as a surrogate measure
of total energy intake) and reported a reduction (14,18) or similar number (43), in response to
the reduced eating window. Evidence from studies by Jakubowicz and colleagues (44,45) has
shown larger morning meals (high in carbohydrate) with small evening meals (high in protein) are effective for reducing body weight and improving glycaemic control. However, in these studies it is difficult to determine whether it is the energy intake or the macronutrient distribution which lead to changes in several physiological outcomes. Neglecting to consider what is being consumed and how frequently in a TRE intervention, while focusing solely on when food is consumed is overlooking a crucial component in understanding the full benefit of TRE. This is particularly important when translating TRE research into practice. Without the information of what food has been consumed, the TRE advice provided to individuals is limited to simply the eating window. Whilst this may help keep the message simple, in practice, individuals will naturally ask what foods they can consume within a specified time. It would be ideal to elucidate the best TRE eating window along with the ideal meal timing and macronutrient composition for optimal results (i.e., combining the what with the when).

The quality of ingested nutrients plays a crucial role when determining any effects of dietary intervention on metabolic health outcomes. For example, carbohydrate-rich foods that have widely different glycaemic index induce different glucose/insulin responses (46). Thus, the quality of the ingested food is also important from a metabolic health perspective (47,48), with dietary guidelines recommending changes to both the quality (i.e. increased grains versus refined foods; whole foods versus processed foods) and the quantity of food (i.e. reduced portion sizes). Only two of the 25 TRE studies reviewed (Table 1) have utilized a measure of dietary quality to assess TRE and compared this to either a 10-min nutrition counselling session (standard dietary advice) (49) or no advice (50). Using the qualitative NOVA classification (51) from free-text annotations of food photos collected throughout a 6-month intervention, Phillips and colleagues (49) reported that participants receiving standard dietary advice significantly increased their intake of unprocessed or minimally processed
foods by 7% and compensated by a reduced intake of processed food, with no changes to fluids consumed. Martens and colleagues (50) used the Healthy Eating Index (52) to obtain an outcome of dietary quality from weeks 3-5 of a 6-week intervention compared to 6 weeks of no advice (following normal diet). Importantly for the comparisons in both studies, the TRE condition did not improve or change dietary quality which was described as “adhering to the protocol” (49) or not adversely affecting dietary intake (50). Detailed dietary analysis that has been performed in several studies has indicated that time-of-day foods, such as late evening snacks and alcohol consumption are reduced with TRE (14,43). If TRE can induce such changes to dietary intake and quality without structured advice, then more rigorous dietary analysis is crucial in future TRE interventions.

**Time-restricted eating: Not just another weight loss intervention**

The primary outcomes of TRE interventions to date have been weight loss, glycaemic control and selected biomarkers of cardiometabolic health, with the majority of studies reporting positive effects on these and several other measures (6,8,9,53,54). However, it is not currently known whether it is the modest energy restriction induced by TRE protocols or the alignment of meal timing with circadian oscillations that induce many of the health benefits of TRE. Not only does circadian phase influence the metabolic response to food intake, food intake itself is under control by the endogenous circadian system (i.e., independent of the sleep/wake and fasting/feeding cycle) (55).

In energy restricted diets that induce weight loss, there is a concomitant reduction in lean mass, typically accounting for at least 25% of the total weight lost (56). The loss of lean tissue during energy restriction can be mitigated by exercise in the face of adequate protein intake (57), but high protein, energy restricted diets are not effective in isolation (58). In the
few TRE studies that have measured body composition, the magnitude of change of lean mass has been small (~1.0 kg) (34) or negligible (32,43,50), usually reflecting a modest loss in body weight, or possibly typical measurement error. Several investigations have combined TRE with exercise training to maximize improvements in body composition (reduced fat mass and maintained or increased lean mass) (59–63). Whether a restricted eating window is optimal to promote adequate rates of protein synthesis to maintain protein balance in the absence of an exercise stimulus is an important question that warrants further research (64). Indeed, whether TRE confers additive benefits to disordered metabolism above and beyond those induced by exercise training remains to be determined experimentally (65).

Dietary interventions are often implemented with the aim of improving glycaemic control. In addition to weight loss, TRE interventions improve fasting glucose concentrations (19,19,24,59), 24-h glucose profiles (determined by continuous glucose monitoring) (21,40), glycated haemoglobin (HbA1c) (38), reduce glucose AUC in response to an OGTT (24,50), reduce nocturnal glucose concentrations (23) (Figure 3), and enhance insulin sensitivity (16,20). Typically, but not always, changes to glucose parameters have been evident in cohorts with elevated glucose concentrations (>5.6 mmol/L) at baseline (i.e. impaired fasting glucose, type 2 diabetes, metabolic syndrome) compared to a lack of change observed in those studies in which these parameters were in the normal range before intervention (16,32,34,40). Furthermore, most of the improvements in glycaemic control measures come from studies of early- or mid-TRE (Table 1). As highlighted by Zhao et al. (66), the distribution of carbohydrate intake across the eating window is a vital when attempting to modify glycaemic control, a factor that should be considered in future studies, and emphasises the need for rigorous dietary assessment in TRE interventions. The range of improvements in glycaemic control across the limited TRE literature to date provides scope
for specific TRE interventions with such markers as primary outcome variables, especially in populations such as individuals with T2D (43), where glucose management is important to minimise diabetes-associated complications and improve health and quality of life.

**Adherence to time-restricted eating**

A major benefit of TRE protocols compared to other dietary interventions is the ability for individuals to adhere to such practices without overt changes on the quality or quantity of dietary intake. This removes some of the stigma and psychological barriers often associated with dietary modification. It has been suggested that over the long term, TRE may be easier to tolerate and implement than other diets approaches (67) as the focus is on *when* rather than *what* to eat. While not all aspects of TRE may encourage adherence (reviewed previously (67)), TRE may offer an option of an alternative dietary strategy to improve metabolic health.

Adherence to TRE in free-living environments has varied from 5 (43) to 6 days per week (16,32) over 4 to 10 week intervention periods, 55% over 12 weeks (18), ~62% over 10 weeks (17) and up to ~84% over 6 (50) or 12 weeks (34). In a sub analysis, Martens et al., (50) measured improved adherence (from 84% to 95% over 6 weeks) when the eating window was extended from 8 h to 8.5 h per day (50). In a supported 8-week intervention, immediately followed by 6-wk of free-living TRE (1200-2000 h) in habitual (3-4 sessions per week) exercisers, Isenmann et al. (63) reported a drop in adherence from 98% (supported) to 71% (self-implementation). Participants in that study (63) rated the ease of TRE implementation as similar to that for a group that followed a traditional macronutrient based diet. While no explanation for these observations was provided, participants in other studies have indicated that if the evening meal time could be delayed slightly, it would improve their adherence (17,43).
Adherence to TRE in studies discussed and summarised in Table 1 is typically from self-report. Studies incorporating objective time-stamped photos are still limited as they rely on participant to accurately capture their meal timing. In support of the self-reported adherence is qualitative responses from participants that mid-TRE as a dietary intervention is achievable on most days of the week (17,23,43), with early-TRE deemed subjectively feasible based on positive health outcomes (20). Although the implementation of these early TRE protocols is challenging with regard to the impact on social and family life, to date, early TRE interventions have not been investigated in free-living conditions. In several studies, investigators have chosen TRE eating windows based on participants personal preferences (i.e., 1200-2000 h) due to both social considerations and the importance of evening meals with family or friends (34–36,59,60). Taken together, there is an underlying narrative of what can be achieved in the real world versus what is most efficacious with regard to optimal meal timing to align with circadian rhythms. There is also unlikely to be a single eating window that will be equally beneficial for every individual, as circadian preferences vary between larks (morning-chronotypes) and owls (night-chronotypes) (68), leading to difficulties in making generic recommendations.

Conclusions and future directions
TRE has become a popular dietary strategy to improve measures of metabolic health, possibly due to a lack of focus on weight loss per se. Indeed, we believe that TRE protocols can be adapted to tackle a variety of pre-existing metabolic conditions dependent on the goals or desired health outcomes of the individual. Further research expanding the use of TRE interventions in different clinical populations under free-living conditions is essential to evaluate long-term adherence and feasibility before recommending additions to national and international diet guidelines. In this regard, we acknowledge that TRE is not the only option,
or dietary strategy in a health professionals toolbox to be used to improve or manage the diverse range of chronic metabolic conditions seen in society. However, we hope this perspective has highlighted the necessity for future studies of TRE to increase the rigour of dietary data collected, assessed, and reported to ensure there is a consistent and standardised approach across TRE interventions. Almost the entire body of dietary literature to date, along with the profession of nutrition science, has focused on what we eat: new knowledge from TRE interventions is shifting that narrative so that now it is vital we also consider that the timing of meals plays an important role in determining metabolic health outcomes. Without consideration of both what and when is eaten, we cannot begin to understand the potential synergies between these two variables and their potential impact on reducing the burden of chronic metabolic diseases at the population level.

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Figure 1. Categorisation of popular diet practices. For chronic energy restriction (CER; 1) during which daily energy intake is reduced by up to 40%, but meal frequency and timing remain unchanged; intermittent fasting (IF; 2), where one day or several days of fasting are interspersed with normal ad libitum eating patterns such that total weekly energy intake is reduced, and meal frequency and timing remaining unchanged on the days of food intake; or time-restricted eating (TRE; 3), in which food is consumed *ad libitum* throughout a set time period, and energy intake may or may not be reduced. In TRE, the daily eating duration (i.e., the time between the first and last energy intake) is typically reduced from a 12–14 h/day ‘eating window’ to ~8-10 h/day.
Figure 2. The three different approaches to time-restricted eating (TRE). A) TRE reduces energy intake as a result of an appropriately timed window of daily energy intake, which reduces time-of-day discretionary foods consumption and induces weight loss; B) TRE does not result in a change in energy intake, but there is an appropriately timed window of energy intake which contributes to improvements in metabolic health independent of any weight loss; or C) TRE does not change energy intake and due to an inappropriately timed eating window little or no health benefits are observed.
**Figure 3.** Representative schematic of glucose concentrations changing over a 24-h period comparing the effects of three meals during a control day (meals over >12 hours; dashed line) with a time-restricted eating pattern (meals within 8 hours; solid line). Redrawn with permission from Parr et al, 2020 (23).
Table 1: Summary of time-restricted eating (TRE) interventions in humans, divided into early (eating window finished before/by 1700 h), mid (delayed breakfast and end of eating window by 1900 h) or late (delayed start of eating window to after 1200 h), and studies whereby the TRE window was self-selected.

| Study                  | Participants (number, sex, age, BMI) | Design               | Intervention                  | Major Findings                      | Diet recording methodology and related outcomes |
|------------------------|--------------------------------------|----------------------|-------------------------------|-------------------------------------|-----------------------------------------------|
| **“Early” TRE** (eating window finishes before/by 1700 h) |                                      |                      |                               |                                     |                                               |
| Hutchison et al, 2019 (24) | 15, M 55 y, 34 kg/m²                  | 1 week RXT (2 wk. w/o) | eTRE: 9 hours, 0800 – 1700 h vs. dTRE: 9 hours, 1200 – 2100 h | ↓ glucose AUC in eTRE and dTRE ↓ fasting glucose by CGM (eTRE) | No diet recording or diet analysis; no data on timing of when participants ate meals. |
| Jamshed et al, 2019 (21) and Ravussin et al, 2019 (22)¹ | 11, M + F 32 y, 30 kg/m²               | 4 days RXT (3.5-5 wk. w/o) | TRE: 8 hours, 0800 – 1400 h vs. Control 12 hours, 0800 – 2000 h | ↑ 24-hour glucose and glycaemic variability via CGM | Meals provided with matched energy at each meal (33% EI), same macronutrients (50% CHO, 30% fat, 15% protein) across day. Same as Sutton et al. (20). |
| Sutton et al, 2019 (20)¹ | 8, M 56 y, 32 kg/m², prediabetes      | 5 weeks RXT (~7 wk. w/o) | TRE: 8 hours, 0800 – 1400 h vs. Control 12 hours, 0800 – 2000 h | ↑ insulin sensitivity ↔ body weight | Meals provided with matched energy at each meal (33% EI), same macronutrients (50% CHO, 30% fat, 15% protein) across day. Same as Jamshed/Ravussin et al., (21,22) |
| Zeb et al, 2020 (33)    | 56, M young (no age)                  | 25 days Pre-Post      | TRE: 8 hours, 0730 – 1530 h | ↓ Chol, TAGs, AST, ALT and Albumin ↑ HDL | No diet recording or diet analysis; no data on timing of when participants ate meals. |
| **“Mid” TRE** (delayed breakfast and early dinner) |                                      |                      |                               |                                     |                                               |
| Gabel et al, 2018 (32) and Gabel et | 23, M + F 49 y, 34.5                  | 12 weeks Pre-Post     | TRE: 8 hours, 1000 – 1800 h | ↔ body weight, fat/lean mass, fasting | 7-day food record at baseline and at week 12; decreased energy |
| Study                      | Participants (number, sex, age, BMI) | Design                  | Intervention | Major Findings                                                                 | Diet recording methodology and related outcomes                                                                 |
|---------------------------|--------------------------------------|-------------------------|--------------|--------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------|
| al, 2020 (69)             | kg/m²                                 | vs. historical control  | glucose ↓ SBP | intake (~1420 kJ/d -20%), NC in macronutrient intake. Self-reported timing of intake |
| Martens et al, 2020 (50) | 22, M+F 67 y, 25 kg/m²               | TRE: 8 hours, starting between 1000–1100 h | ↔ vascular endothelial function, body weight, fat/lean mass, BP ↓ hunger | Energy intake (via 24 h diet record ASA24, once per week) was unchanged, diet quality (through HEI) unchanged. Self-reported timing of intake. |
| Parr et al, 2020 (43)    | 19, M + F 50 y, 34 kg/m², type 2 diabetes | TRE: 9 hours, 1000 – 1900 h | ↔ body weight, fat/lean mass, HbA1c, fasting glucose | Food records throughout entire 2-week baseline and 4-week study. N/C to dietary intake with TRE (vs baseline). Photos to capture dietary timing. Reduced EI on adherent TRE days vs non-adherent (reduced CHO, alcohol). |
| Parr et al, 2020 (23)1    | 11, M 38 y, 32 kg/m²                  | TRE: 8 hours, 1000 – 1800 h vs. Control: 15 hours, 0700 h – 2200 h | ↔ 24-h glucose concentrations or AUC (CGM), insulin ↓ nocturnal glucose concentrations | Meals provided; 25:30:45% EI; same macronutrients at each meal (30% CHO, 50% fat, 20% protein). Self-reported timing of intake at structured times. |
| Peeke et al, 2021 (19)2   | 60, M + F 44 y, 38 kg/m²              | TRE: 10 hours (self-selected from 0700–1700 h to 1000 – 2000 h) vs. Control 12 hours | ↓ body weight (-10.7 kg) in TRE vs. CON (-8.9 kg), fasting glucose (when FBG >5.5 mmol/L) | Controlled meals/energy intake (reduced energy intake by 500-100 kJ/d) via Jenny Craig Rapid Results Program and purchasing 8 weeks of food. No reporting of timing of intake. |
| “Late” TRE (after 1200 h start) |                                      |                         |              | 7-day food record at baseline and week 8. Household measures and                |
| Cienfuegos et al, 2020 (16) | 58, M + F 47 y, 36 kg/m²              | TRE: 4 hours (from 1500 h) and 6 hours | ↓ body weight (3.9 and 3.4%) in TRE | 7-day food record at baseline and week 8. Household measures and |
| Study                          | Participants (number, sex, age, BMI) | Design                          | Intervention                                      | Major Findings                                                                 | Diet recording methodology and related outcomes                      |
|-------------------------------|--------------------------------------|---------------------------------|--------------------------------------------------|---------------------------------------------------------------------------------|------------------------------------------------------------------------|
| Cienfuegos et al, 2021 (70)   |                                      |                                 | (from 1300 h) vs. Control, ad libitum            | groups vs. Control (0.1%) ↔ fasting glucose, HbA1c ↔ body weight, pre vs postmenopausal women | self-reported times. Decreased EI in both groups (~2090 kJ/d) compared to Control (~420 kJ/d). N/C to sugar, saturated fat, cholesterol, fiber, or sodium intakes. |
| Isenmann et al, 2021 (63)     | 35, M + F 27 y, 26 kg/m²             | 14 weeks (+2 week baseline) RCT  | TRE: 8 hours, 1200 – 2000 h vs. Macronutrient-Based Diet (MBD) | ↓ body weight (~5%) in both TRE and MBD groups ↓ body fat ↔ lean mass          | Food records throughout entire 2-week baseline (phase 1) and 8-week phase 2, encouraged for 6-week phase 3. N/C to dietary intake with TRE or MBD (vs baseline). |
| Kotarsky et al, 2021 (60)     | 21, M + F 44 y, 30 kg/m²             | 8 weeks RCT                      | TRE: 8 hours, 1200 – 2000 h vs. Control, normal diet pattern | ↓ body weight in TRE (3.3%) vs. Control (0.2%)                                   | 3-day diet records collected at weeks 1, 4 and 7. Participants were excluded after more than 1 non-compliant (to the timing of eating) day. Decreased EI in both groups (~1250 kJ/d) due to decreased CHO intake. |
| Lowe et al 2020 (34)          | 105 M + F (online), including 46 (in person) 46 y, 31 kg/m² | 12 weeks RCT                     | TRE: 8 hours, 1200 – 2000 h vs. Consistent meal timing (CMT) (0600-1000 h breakfast, 1100-1500 h lunch, 1700-2200 h dinner) | ↔ body weight (-0.9 vs. CMT: -0.6 kg), ↓ appendicular lean mass index in TRE vs. CMT | No diet recording or diet analysis; no data on timing of when participants ate meals. |
| Moro et al, 2016              | 34, M                                 | 8 weeks RCT                      | TRE: 8 hours, 1300                                | ↓ fat mass (-16%) vs.                                                          | Participants were instructed to |
| Study                        | Participants (number, sex, age, BMI) | Design                     | Intervention | Major Findings                                                                 | Diet recording methodology and related outcomes |
|------------------------------|--------------------------------------|----------------------------|--------------|--------------------------------------------------------------------------------|-----------------------------------------------|
| (59)<sup>3</sup>            | 29 y, 27 kg/m²                       | RCT                        | – 2000 h     | Control (-2%), fasting glucose, fasting insulin, ↔ lean mass                   | consume three meals, based off their baseline (7-d recording) dietary intake. TRE was 40%, 25% and 35% EI at the three meals (1 pm, 4 pm and 8 pm) vs. Control of 25% at 8 am, 40% at 1 pm and 35% at 8 pm. ND between groups for EI or macronutrient intake. |
| Schroder et al 2021 (35)    | 32, F 39 y, 33 kg/m²                 | 3 months Non-randomised CT | TRE: 8 hours | ↓ body weight (-3.4 kg) vs. Control (+1.3 kg)                                   | No diet recording or diet analysis; no data on timing of when participants ate meals. |
| Smith et al, 2017 (36)      | 20, F 21 y, ~65 kg (No BMI data)     | 4 weeks Pre-Post           | TRE: 8 hours | ↓ body weight (0.6 kg)                                                         | Self-reported adherence to the diet prescription but no analysis of diet energy intake or data on the timing of when participants ate meals. |
| Stote et al, 2007 (31)<sup>1</sup> | 15, M + F 45 y, 23 kg/m²             | 8 weeks RXT (11 wk. w/o)   | TRE: 4 hours | ↓ body weight (1.4 kg), ↑ blood pressure vs. Control                           | Meals provided (~9890 kJ/d TRE and 10160 kJ/d in Control), same macronutrient intake (50% CHO, 35% fat, 15% protein). |
| Tinsley et al, 2017 (61)<sup>3</sup> | 18 M Normal weight                   | 8 weeks RCT                | TRE: 4 hours | ↔ body weight, fat mass                                                        | -2720 kJ/d energy reduction each day of TRE (non-training days) |
| Tinsley et al, 2019 (62)<sup>3</sup> | 40 F 22 y, 23 kg/m²                  | 8 weeks RCT                | TRE: 8 hours | ↑ body weight (both groups), ↓ fat mass                                       | Weighed diet records on selected weekday and weekend days |
| Study                  | Participants (number, sex, age, BMI) | Design | Intervention | Major Findings                                                                 | Diet recording methodology and related outcomes                                                                                                                                 |
|-----------------------|--------------------------------------|--------|--------------|--------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                       |                                      |        |              | (~4%) TRE vs. CON, ↑ muscle strength & endurance (both groups)                  | during pre- and two separate weeks during intervention period. Increased EI in all groups (~84-840 kJ/d).                                                                                                                                                              |
| **Participant choice TRE (no specified “window”)** |                                      |        |              |                                                                                   |                                                                                                                                                                                                                                                                  |
| Anton et al, 2019     | 10, M + F                            | 4 weeks| TRE: 8 hours, self-selected | ↓ body fat (-0.6 kg, 0.7%)                                                        | Food diaries collected for adherence (84%, in weeks 2-4). No analysis of dietary intake.                                                                                                                                                                             |
| (37)                  | 77 y, 34 kg/m²                       | Pre-Post|              |                                                                                   |                                                                                                                                                                                                                                                                  |
| Antoni et al, 2018    | 13, F                                | 10 weeks| TRE: 90 min earlier dinner and 90 min later breakfast, self-selected | ↔ body weight (-0.7 vs. -0.5 kg), ↓ body fat percentage                            | Validated food diaries used for the entire intervention period. Diet timing via self-report in food diaries. Decreased EI by ~2930 kJ/d.                                                                                                                                  |
| (17)                  | 46 y, 29 kg/m²                       | Pre-Post|              |                                                                                   |                                                                                                                                                                                                                                                                  |
| Cai et al, 2019       | 271, M + F                           | 12 weeks| TRE: 8 hours, self-selected, vs. ADF vs. Control | ↓ body weight (-3.6 kg) in TRE (and -4.5 kg in ADF) vs. Control                  | All groups were prescribed energy restricted diet intake, with the TRE group being provided one meal in the 8 h period. No reporting of baseline energy intake, self-reported intake during intervention (weeks 4 and 12), with eating times.                                                                                                                                 |
| (41)                  | 34 y, 26 kg/m² NAFLD                 | RCT    |              |                                                                                   |                                                                                                                                                                                                                                                                  |
| Chow et al, 2020      | 20, M + F                            | 12 weeks| TRE: 8 hours, self-selected (achieved 10 h) vs. Control 15 h                   | ↓ body weight (3.7% ~3.6 kg) in TRE vs. Control                                    | Energy intake logged using MCC app to obtain meal timing. Number of eating occasions reported, as a surrogate measure of diet intake. TRE eating window selected ~1040 – 1840 h with 55% adherence.                                                                                           |
| (18)                  | 45 y, 34 kg/m²                       | Pre-Post|              |                                                                                   |                                                                                                                                                                                                                                                                  |
| Gill and Panda,       | 8, M+F                               | 16 weeks| TRE: 10 hours, self-              | ↓ body weight (-3.3)                                                             | Custom mobile app (MCC) to                                                                                                                                                                                                                                          |
|                       |                                      |        |              |                                                                                   |                                                                                                                                                                                                                                                                  |
| Study | Participants (number, sex, age, BMI) | Design | Intervention | Major Findings | Diet recording methodology and related outcomes |
|-------|----------------------------------|--------|--------------|----------------|-----------------------------------------------|
| 2015 (14) | 27 y, 33 kg/m² | Pre-Post | selected | ↓ body weight (-1.7 kg), ↓ waist circumference, ↓ HbA1c | take photos of food for entire period. Annotated and analysed using FDDNS or CalorieKing. EI decreased by 20.26% (-4.92-35.6% 95%CI) |
| Kesztyus et al, 2019 (38) | 40, M + F 49 y, 31 kg/m² | 12 weeks Pre-Post | TRE: 8 hours, self-selected | ↓ body weight (-1.7 kg), ↓ waist circumference, ↓ HbA1c | Self-reported intake of main diet components rated on 6-point Likert scale (never – several times a day) at baseline and post-intervention. No diet intake reporting or analysis. Self-reported timing of eating (time of first and last meal) using a diary. |
| Kesztyus et al, 2021 (39) | 63, M+ F 48 y, 26 kg/m² | 12 weeks Pre-Post | TRE: 8-9 hours, self-selected | ↓ body weight (-1.3 kg), ↓ waist circumference (-1.7 cm), ↑ HRQoL | Self-reported adherence (~72%) via time of first and last meal. No diet intake reporting or analysis. |
| LeCheminant et al, 2013 (15) | 27, M 21 y, 24 kg/m² | 2 weeks RXT (1 wk. w/o) | TRE: 0600 – 1900 h vs. Ad libitum | ↓ body weight (-0.4 kg) vs. ad libitum (+0.6 kg) | 3-day diet recall (two weekdays, one weekend) during each week using 24-h multi pass recall. Reduced EI in TRE vs ad libitum, no differences in macronutrient intake. Self-reported timing of intake. |
| McAllister et al, 2020 (71) | 22, M 22 y, 28 kg/m² | 4 weeks RCT | TRE: 8 hours, self-selected vs. either ad libitum or prescribed isoenergetic | ↔ body weight ↓ body fat, ↓ BP | Self-reported time of first and last meal, diet intake logged using MyFitnessPal. Trend (P=0.054) for higher diet intake in the ad libitum TRE group compared to |
| Study                  | Participants (number, sex, age, BMI) | Design                  | Intervention                                                                 | Major Findings                               | Diet recording methodology and related outcomes |
|-----------------------|--------------------------------------|-------------------------|------------------------------------------------------------------------------|-----------------------------------------------|------------------------------------------------|
| Phillips et al, 2021 (49) | 213 M + F (observation), 40 y, 25 kg/m² 54, M + F (RCT) 43 y, ~28 kg/m² | 1-month observation 6 months RCT | TRE: 12 hours, self-selected vs. Standard Dietary Advice (SDA; 10 min nutrition counselling) | ↓ body weight (TRE:1.6% vs. SDA:1.1%)                                      | Diet intake logged using MCC app (for timing), text coded for dietary quality analysis using NOVA (unprocessed to processed) categories. No analysis of energy intake. |
| Pureza et al, 2020 (72)     | 58, F 31 y, 33 kg/m²                   | 3 weeks Pre-Post                    | TRE: 12 hours, self-selected vs. Unrestricted (Control) | ↓ body weight (-1-2 kg in both groups), ↓ body fat in TRE | No measurement of diet timing but energy reduction (prescribed) was similar in both groups (-2680 kJ/d) |
| Wilkinson et al, 2019 (40)  | 19, M + F 59 y, 33 kg/m²               | 12 weeks Pre-Post                  | TRE: 10 hours, self-selected                                                 | ↓ body weight (-3 kg (-3%) ), fat mass, BP ↔ fasting glucose, insulin, HbA1c | Diet intake logged using MCC app (for timing), estimated -9% (840 kJ/d) energy reduction but no analysis of macronutrient intake. |

Key: 'provided meals (isoenergetic); 'prescribed diet (hypoenergetic); 'exercise protocol with TRE/CON; arrows indicate significant reductions (↓) or no significant changes (↔). ADF, alternate day fasting; ALT, Alanine transaminase; ASA24, Automated Self-Administered 24-hour dietary assessment tool; AST, aspartate aminotransferase; BP, blood pressure; CGM, continuous glucose monitor; CHO, carbohydrate; CMT, consistent meal timing; EI, energy intake; dTRE, delayed time-restricted eating; eTRE, early time-restricted eating; F, females; FBG, fasting blood glucose; FDDNS, Food and Nutrient Database for Dietary Studies; HbA1c, glycated haemoglobin; HDL, high density lipoprotein; HEI, healthy eating index; HRQoL, health-related quality of life; M, males; MBD, macronutrient based diet; MCC, MyCircadianClock; MetS, metabolic syndrome; NAFLD, non-alcoholic fatty liver disease; N/C, no change; RCT, randomised controlled trial; RXT, randomised crossover trial; SBP, systolic blood pressure; SDA, standard dietary advice; TAGs, triglycerides; TRE, time-restricted eating; w/o, washout.