Chrononutrition and Endocrine Contributors to Gestational Glycemic Control and Infant Birth Weight

by

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# Dedication

This dissertation is dedicated to all who made this work possible, which is an impossibly long list. I thank my partner for making so many sacrifices that facilitated me reaching for my dreams as a scientist and for keeping me alive during this ever-challenging process. I thank my family for always supporting life-long learning and pushing me to pursue my passions to their fullest extent. I thank the educators who have not only imparted their wisdom, but have motivated me to evolve as a critical thinker and who told me I had a place in the academy when I constantly felt I didn’t. And finally, I thank my dogs, for keeping me sane and still wanting anything to do with me after spending years on this project.

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# Abstract

The guidelines for the abstract are stated in *The Dissertation Handbook*, provided by Rackham, and are included below:

The abstract provides an overview of the purpose and focus of the dissertation—the problem, research issues and questions—and a presentation of arguments, methods or procedures used. It should summarize the evidence, results or findings. An abstract of up to 550 words is required as part of the dissertation. At the final dissertation submission, the text of the abstract (with no special characters) is required to be entered into the online submission system.” (Rubin 6).

You should replace this text with your own abstract, created to fit within the guidelines stated above.

# Chapter 4: Gestational Early-Time Restricted Feeding Results in Sex-Specific Glucose Intolerance in Adult Male Mice

## Abstract

The timing of food intake is a novel dietary component that impacts health. Time-restricted feeding (TRF), a form of intermittent fasting, manipulates food timing. The timing of eating may be an important factor to consider during critical periods, like pregnancy. Nutrition during pregnancy, too, can have lasting impact on offspring health. The timing of food intake and has not been thoroughly investigated in models of pregnancy, despite evidence that interest in the practice exists. Therefore, using a mouse model, we tested the effects of gestational early TRF (eTRF) over the life course of male and female offspring and after high fat, high sucrose (HFHS) diet challenge. Body composition was similar between groups in both sexes from weaning to adulthood, with minor increases in food intake in eTRF females and slightly improved glucose tolerance in males. After 10 weeks of HFHS, male eTRF offspring developed glucose intolerance. Further studies should assess the susceptibility of males, and apparent resilience of females, to gestational eTRF related changes in islet physiology and HFHS diet in adulthood.

## Introduction

All mammals have cell-autonomous clocks that coordinate the rhythm of metabolism. The molecular clock consists of the CLOCK:BMAL1 heterodimer that binds to regulatory elements in DNA (E boxes), among them are its own repressors cryptochrome (1 & 2) and period (1-3) (1). The nuclear hormone receptors ROR(α, β, and γ) and REV-ERB (α and β) activate or repress expression of BMAL1 respectively (2, 3). This highly coordinated transcription factor system entrains circadian rhythm in the central clock, the suprachiasmatic nucleus (SCN) of the brain, according to external cues. Peripheral tissues also possess internal clocks that can be entrained. This system is imparts a rhythm of metabolism, programming predominance of melatonin during the night hours and cortisol/corticosterone during early waking hours (2). Factors capable of manipulating, or entraining, this system are called zeitgebers. One such potent zeitgeber is food intake (4).

The timing of food intake in reference to circadian rhythms can impact propensity for health or disease (5). Time-restricted feeding/Eating (TRF/E), a method of intermittent fasting, is thought to align caloric intake with naturally occurring circadian rhythms of metabolism, acting as a zeitgeber. Timing of food intake is capable of programming metabolic systems for either poor health from chronodisruption, or good health with either diurnal or nocturnal feeding, depending on the species.

To our knowledge, no estimate of the prevalence of TRE in humans exists. However, according to one sample, up to ten percent of people surveyed that stated they followed a diet in the year 2020 had attempted “intermittent fasting,” making it the most prevalent dietary intervention in that sample (6). There are critical periods of development in the lifespan where changes to dietary behaviors can impact current and future health status. One such critical period is pregnancy. During pregnancy, habitual timing of food intake may be altered for many reasons: religious practice, food insecurity, disordered eating behaviors, nausea and vomiting of pregnancy/morning sickness, changes in taste/food preferences, or intentional timing of eating for weight maintenance. Very little research has evaluated the timing of eating during pregnancy and its impact on offspring health. One cross-sectional analysis found that extending the overnight fast during pregnancy was associated with lower blood glucose levels at mid gestation (7). Another recent work demonstrated that up to 23.7% of a human pregnant and recently post-partum cohort said they would be willing to try TRE during pregnancy (8). However, there is currently no information on the long-term implications of this dietary strategy for progeny. The most available literature examines fasting during the month of Ramadan while pregnant. Review of these studies found that children born to those who fasted during pregnancy have similar birth weights and rates of pre-term birth as those who did not fast (9). In a recent review, Ramadan exposure *in utero* was associated with smaller body size and stature in later periods of life (10). However, these studies are limited and Ramadan fasting is an imperfect model for TRF, as food intake is not only limited in duration but also not permitted during the normal active phase for humans.

There is much interest in the TRE diet and interruptions in food intake are known to occur during pregnancy; however, research about the effects of intentional fasting during pregnancy is limited to the observance of Ramadan, a cross-sectional study about attitudes toward the practice (8), and one case report of fasting to improve gestational diabetes (11). Detailed modeling of TRF in pregnancy is warranted, as TRE is currently thought to exist in human populations (8, 11) yet, long-term effects are unknown.

Previous studies of maternal diet during pregnancy have focused on dietary restriction or macronutrient excess in pregnancy, with little-to-no attention directed toward temporality of food intake. At the time of this manuscript, two studies of TRF during pregnancy in rodents exist. The first emphasized fetal health and was completed in the context of preventing complications from a high fat, high sucrose diet (HFHS) during gestation in a rat model. Upadhyay and colleagues found that 9-hour TRF improved fetal lung development (12) and placental oxidative stress markers (13) at embryonic day (E)18.5 compared to ad libitum fed dams. This approach did not evaluate the long-term, postnatal effects of TRF and the independent effects of TRF are complicated by the use of a high fat, high sucrose diet. The second, also in rats, evaluated 12 hour access in light and dark cycles to a chow diet during pregnancy and followed male and female resultant offspring until 150 days of age (14). Adult female offspring of dams fed in the dark cycle with TRF were found to be glucose intolerant *in vivo*, and reduced glucose stimulated glucose secretion *in vitro* in both male and female offspring islets. altered glucose metabolism in adult offspring of TRF fed dams (14). However, this study compared 12 hour feeding to ad libitum feeding in pregnancy, leaving more restrictive windows unexamined.

The effects of TRF in non-pregnant human populations are inconsistent. Some TRF trials result in significant weight loss (15–18) while others do not (19–21). Similarly, insulin sensitization results in some (15, 21–24), but not all trials of TRF (16, 20). The way TRF is employed in human studies is rarely consistent, with varying lengths of feeding window (4-12 hours), timing of feeding window (early vs late), control of caloric intake (isocaloric vs ad libitum feeding), and inpatient observation or outpatient adherence monitoring. As such, the biological effects of this eating strategy are not clear, even in non-pregnant humans.

Results from rodent models of TRF are more consistent than human trials. These have found TRF of a HFHS reduces body weight compared to ad libitum feeding (25–30), can improve Homeostatic Model Assessment for Insulin Resistance (HOMA-IR) (27, 30, 31), and may limit complications like insulin resistance (28, 29) from HFHS feeding.

Taking together the likelihood that food intake can be time-disrupted in pregnancy and the evidence of TRF being a potent method to improve body composition and glycemic health in adult mice, we sought to evaluate the impact of TRF of normal laboratory chow (6-hour, early dark-cycle) before and during pregnancy on resulting offspring body composition and glycemic health through adulthood.

## Methods

### Animal Care and Use

Female C57BL/6J mice were obtained from Jackson Laboratory (RRID IMSR\_JAX:000664). All animals were maintained on a, 12-hour light/dark (12 dark (ZT12, 6pm):12 light (ZT0, 6am); ZT = zeitgeber time) cycle in a temperature and humidity-controlled room. After one week of acclimatization, they were single-housed and were assigned to feeding groups. Dams were randomized to either early time-restricted feeding (eTRF) or *ad libitum* (AL) feeding during gestation (n 8= eTRF, 9=AL). This study was completed in two independent cohorts of animals. The phenotypes noted in offspring were highly consistent between cohorts. Therefore, data shown is the combined total from cohorts one and two and statistical tests do not include effects of cohort in the model. Dams fed AL had 24-hour access to a chow diet (NCD, Picolab Laboratory Rodent diet, 5L0D; 5% of Calories from fat, 24% from protein, 71% from carbohydrates). Dams fed eTRF had 6 hours of NCD food access during the early dark cycle (ZT 14-ZT 20). Water was provided *ad libitum* throughout the study to both experimental groups. After one week of either AL or eTRF feeding (beginning age 120 days), age-matched males were introduced into cages for breeding. Males were kept in the cage until a copulatory plug was detected. Daily, dams were transferred to a clean cage at ZT20, allowing for a cage free of food for eTRF animals and similar levels of handling between experimental groups. After birth, all dams switched to AL and were maintained on this diet until weaning at postnatal day (PND) 21.5. Therefore, any phenotype in the offspring is attributable to modifications to the pre-gestational/gestational diet. All experimental protocols were reviewed and approved by The University of Michigan Institutional Animal Care and Use Committee.

### Offspring growth and food intake monitoring

Pups born were weighed and counted within 24 hours of birth. Litters were reduced to 4 pups (2 male, 2 female, when possible) at PND 3.5 to standardize milk supply between litters. At PND 21.5, offspring were weighed and body composition was assessed using EchoMRI 2100 (EchoMRI) before being weaned by sex and maternal feeding regimen and housed 4-5 per cage (eTRF males = 11, eTRF females = 19, AL males = 16, AL females =17). Offspring were given AL access to NCD until PND 70. Food intake and body composition were assessed weekly. Food intake is represented as an average per animal per day. After PND 70, all animals began AL 45% High Fat, High Sucrose Diet (HFHS; Research Diets D12451; 45% Fat/ 20% Protein/ 35% Carbohydrate). Weekly body composition and food intake measurement continued during HFHS feeding.

### Insulin tolerance and glucose tolerance testing

Baseline intraperitoneal insulin (ITT) and glucose tolerance tests(GTT) were assessed at young adulthood towards the end of the NCD diet period (PND 60-70, in that order). Animals were transferred into a cage with no food during the early light cycle (ZT 2), with water freely available. After 6 hours, fasting blood glucose was assessed using a tail clip and a handheld glucometer (OneTouch Ultra). Shortly thereafter, an intraperitoneal injection of insulin was administered (Humulin, u-100; 0.75U/kg lean mass). Blood glucose was assessed by glucometer every 15 minutes for 2 hours. One week later, glucose tolerance was assessed in a similar way (D-Glucose,1.5g/kg lean mass). Insulin and glucose tolerance were then re-assessed after HFHS feeding (PND 140-160) (insulin dose 2.5U/kg lean mass, glucose dose 1.0g/kg lean mass). Area under curve was calculated for each animal by taking the sum of glucose at each time point, and then was averaged by sex and maternal feeding regimen. Rates of drop for ITT were calculated by limiting the dataset to the initial period after insulin administration (<60 minutes), taking the log of the glucose values and generating a slope for each animal. After each animal’s rate of drop was calculated, values were averaged by sex and treatment.

### Glucose stimulated insulin secretion

One week after GTT and ITT, animals underwent intraperitoneal glucose stimulated insulin-secretion (GSIS) testing (PND 160-170). At ZT2, animals were placed in a clean cage without food and with unrestricted access to water. After a 6-hour fast, animals were lightly anesthetized with isoflurane via drop jar and a baseline blood sample was collected via retro-orbital bleed with a heparinized capillary. Following baseline blood collection, an intraperitoneal injection of D-glucose (1.0g/kg lean mass) was given. After 15 minutes, animals were lightly anesthetized in the same manner and another blood sample was collected. Blood samples were allowed to clot on wet ice (~20 minutes), then were spun down in a cold centrifuge (4° C, Eppendorf microcentrifuge, model 5415R) for 20 minutes at 2000 g. Serum was pipetted off and stored at -80 °C until analysis. Serum insulin was assessed via a commercially available ELISA kit (ALPCO 80-INSMSU-E10). Insulin was assessed in 5uL of serum and read via colorimetric assay.

### Statistical analysis

All measures with p-values <0.05 were considered statistically significant. Data are presented as mean +/- standard error throughout. All statistical analyses were performed using R version 4.0.2 (32). Repeated measures, such as body composition, cumulative food intake, and responses to GTT or ITT were assessed via mixed linear effects modeling with random effects of mouse ID and dam and fixed effects of maternal dietary treatment, age, and sex using lme4 version 1.1-26 (33). Body composition and food intake were measured separately in 2 phases: during NCD feeding, and after being switched to HFHS. Analyses were tested for significant interactions between sex and maternal dietary treatment. Models were assessed using a two-way ANOVA for sex and maternal dietary treatment, with an interaction between the two. If a significant interaction was observed, sex-stratified models were then used and the p-value for the interaction was reported. Otherwise, sex was used as a covariate in a non-interacting model. Observations were tested for normality by Shapiro-Wilk test and equivalence of variance by Levene’s test. Pairwise measures that were normal and of equal variance utilized Student’s *t*-tests. Measures that were not normally distributed used non-parametric Mann-Whitney tests.

## Results

### Gestational eTRF increases food intake, but not body weight in early life

To model gestational early time restricted feeding (eTRF), we used a normal chow diet (NCD) and assigned female mice to either unrestricted (*ad libitum,* AL) or 6 hours of restricted food availability between ZT14-20 (eTRF) (**Figure 1A**). This period represents the active phase of both pregnant and non-pregnant mice(34). This approach limits potential sleep disruptions and is more translationally relevant to human dietary restriction. This treatment started a week before mating and continued through delivery (**Figure 1B**). We find no evidence of maternal eTRF causing significantly lower daily food intake during pregnancy nor are there changes in body weight (Supplementary Figure 1A&B). Litters were normalized to equal sizes to reduce variability and effects of lactation.



Figure **: Experimental Protocol and Timing**

**A)** Food availability and timing for dams during pregnancy. Food access began at ZT13 for early Time-Restricted Feeding dams (eTRF, light gray, n=8) and continued until ZT129, total of 6 hours. Food was available 24 hours a day for ad libitum dams (AL, dark gray, n=9). **B)** Offspring experimental protocol. After birth, all dams had AL access to laboratory chow (NCD). Litters were reduced to 4 (2 males, 2 females when possible) on post-natal day (PND) 3. Offspring were weaned by maternal feeding regimen at PND 21 and maintained on AL NCD for 70 days. Weekly body composition and food intake measurements were taken throughout the experiment. At 70 days of age, insulin tolerance tests (ITT) and glucose tolerance tests (GTT) were conducted before switching all animals to a 45% high fat, high sucrose diet (HFHS) with sucrose. Animals were on HFHS for 10 weeks before repeating ITT and GTT, and an in vivo glucose stimulated insulin secretion test (GSIS). Animals were euthanized after these tests. Abbreviations: zeitgeber time (ZT), ZT0 = lights on, ZT12 = lights off.

The pups resulting from this experiment were weighed and their body composition was assessed weekly, then analyzed using linear mixed effect modeling. We found significant and expected effects of age and sex (older mice weigh more than younger mice and male pups weigh more than females), but no effect modification of maternal eTRF on body weight (**Figure 2A,** pdiet=0.47), lean mass (**Figure 2C,** pdiet=0.45), or fat mass (**Figure 2B**, pdiet=0.47). There was no interaction between sex and maternal feeding regimen in cumulative food intake (pdiet\*sex=0.38). However, cumulative food intake in the NCD period is 22% higher in eTRF females than AL females and 10% higher in eTRF males than AL males (**Figure 2D**, pdiet = 0.016). Assessing the efficiency by which food is converted into stored mass resulted in a 12% reduced feeding efficiency in eTRF female offspring (psex<0.00001) which is not present in males (**Supplementary** **Figure 2A**).



Supplemental Figure : **Maternal Food Intake and Body Weight during Gestation**

**A)** Maternal food intake from one week before pregnancy until delivery B) Maternal body weight from one week before pregnancy until delivery. Dams in analysis n 8= eTRF, 9=AL.

### Gestational eTRF modestly improves glucose tolerance in young adult males

To assess glucose homeostasis in the offspring, we conducted ITTs and GTTs between PND 60 and 70. Male offspring averaged 15mg/dL higher blood glucose during insulin tolerance testing compared to females (psex=0.0018), but no effect of maternal dietary restriction was evident through linear mixed effect modeling (**Figure 2E**, pdiet=0.73). Summarizing the ITT by calculating the area under the curve (AUC) demonstrated there was no diet:sex interaction (pdiet:sex=0.069), but an effect of maternal restriction where eTRF offspring had lower AUC compared to AL offspring, 8.5% and 2.2% lower in females and males respectively (pdiet=0.013), and a significant effect of sex (psex<0.0001). As expected, males had a higher AUC than females (**Figure 2F**). The initial response to insulin (the rate of glucose decline over the first 60 minutes, not pictured) was not significant for sex (psex=0.10) or treatment (pdiet=0.83). These data suggest that gestational eTRF slightly improves the response to insulin challenge in adult mice, and that this is not driven by increased fat mass.

Glucose tolerance was similar in young adulthood between groups in both males and females (**Figure 2G**). We found no significant effect of diet (pdiet=0.53) on the rise in blood glucose during GTT, but there was an effect of sex (psex=0.0093) on glucose tolerance, again with expected higher glucose levels in male mice. The summarized AUC for the GTT (**Figure 2H**) shows a significant interaction between sex and maternal dietary treatment (psex:diet=0.00082). eTRF males had an 8.2% lower AUC than their AL counterparts (pdiet<0.0001) while this was absent in females (pdiet=0.99). Fasting blood glucose, assessed before ITT and GTT, was 10.4% higher in males than in females (psex=0.0054; **Figure 2I**), but did not differ significantly by maternal dietary treatment (pdiet=0.18). Taken together these data suggest that gestational eTRF has very a mild effect on adult offspring, despite the narrow feeding window. Offspring whose mothers were fed eTRF had slightly improved responses to insulin and glucose challenge but no differences in body weight or in fat mass.



Figure : **Early Life Body Composition, Food Intake, and Glycemic Homeostasis**

**A)** Body weight in grams from PND21-PND70 in males and females, averaged by age, maternal feeding regimen, and sex. **B)** Fat mass in grams from PND21-PND70 in males and females, averaged by age, maternal feeding regimen, and sex. **C)** Lean mass in grams from PND21-PND70 in males and females, averaged by age, maternal feeding regimen, and sex. **D)** Food intake in kcals per mouse per day, averaged by week, maternal feeding regimen, and sex. \*p-value <0.05 for diet. **E)** Insulin tolerance test (ITT) ~PND 70, averaged by maternal feeding regimen, sex, and time in minutes. **F)** Area under the curve (AUC) for ITT, averaged by maternal feeding regimen, and sex. \* indicates p-value <0.05 for effect of diet in males. **G)** Glucose tolerance test (GTT) ~PNG 70, averaged bymaternal feeding regimen, sex, and time in minutes. **H)** AUC for GTT, averaged by maternal feeding regimen, and sex. \* indicates p-value <0.05 for effect of diet in males. **I)** Fasting blood glucose (FBG) PND 70, averaged by maternal feeding regimen and sex. Animals included in body composition measurements, FBG, ITT, and GTT, n=11 eTRF males, 16 AL males, 19 eTRF females, 17 AL females. Number of cages in food intake analysis n=4 eTRF males, 5 AL males, 4 eTRF females, 5 AL females.

### HFHS feeding in adult offspring exposed to eTRF during gestation generates sex-specific glucose intolerance

Given that adult offspring were minimally affected by gestational eTRF exposure, we administered a high fat, high sucrose (HFHS) overnutrition challenge; *ad libitum* access to 45% of energy from fat and 17% of energy from sucrose after PND 70. Food intake and body composition measurements continued weekly. The average weekly food intake increased by 67.6% in AL offspring and by 31.8% in eTRF offspring after switching to HFHS, both of which exceed energy needs for adult mice (35). Similar to the findings on chow, with HFHS, there were no major differences between eTRF and AL offspring in body weight (**Figure 3A**, pdiet=0.99), fat mass (**Figure 3B,** pdiet=0.65), or lean mass (**Figure 3C,** pdiet=0.47). Therefore, offspring of eTRF and AL experienced similar changes in body composition in response to overnutrition. Cumulative HFHS consumption was comparable between females and males (psex=0.72), and maternal restriction groups (**Figure 3D**, pdiet=0.72). Feeding efficiency was greater in males than in females, which is consistent with the NCD period (**Supplemental Figure 2B,** psex = 0.00023). However, unlike the NCD period, efficiency was indistinguishable between eTRF and AL offspring (pdiet=0.93).



Supplemental Figure : **Feeding Efficiency Throughout Adulthood**

**A)** Feeding efficiency (%) in males and females, calculated based on food intake and body composition changes during the NCD period (before PND 70). (psex<0.001, pdiet=0.002). **B)** Feeding efficiency in males and females during the HFHS period (after PND 70). (psex = 0.00023, pdiet = 0.093).

We repeated an ITT and GTT after 10 weeks of HFHS feeding. During the ITT, there was a significant interaction between sex and diet using mixed linear effect modeling (**Figure 3E**, psex:diet=0.03). Female eTRF had a similar response to insulin, with less than a 1 mg/dL difference from their AL counterparts (pdiet=0.85), but male eTRF offspring tended to be more insulin sensitive with 25mg/dL lower glucose compared to AL males (pdiet=0.17). It could also be true that females were more resilient to changes from HFHS. These findings were confirmed by calculating the AUC where eTRF females showed no difference in AUC compared to AL females (**Figure 3F**, pdiet=0.20) while eTRF males had 20.4% lower AUC than AL males (pdiet<0.0001). The initial rate of glucose decline (not pictured) was greater in females compared to males (psex=0.029) but there were no differences between eTRF and AL offspring (pdiet=0.23). The trend toward insulin sensitivity from the ITT was not explained by fasting blood glucose, as females had 23% lower fasting blood glucose than males (psex<0.0001) but were similar between eTRF and AL offspring within the same sex (**Figure 3I,** pdiet=0.83). Glucose tolerance tests in **Figure 3G**, also showed significant effect of interaction (psex:diet=0.011), although now in the opposite direction. During GTT, eTRF males trended toward glucose intolerance with an average of 53mg/dL higher glucose than AL males during the course of the experiment (pdiet=0.14). This was not observed in female eTRF offspring, which had similar blood glucose during the GTT compared to AL females (pdiet=0.61). The GTT AUC showed interaction between effects of sex and treatment (**Figure 3H,** (psex:diet<0.0001)). AUC was 5% lower in eTRF females (pdiet=0.07) but was 13.5% higher in eTRF male offspring compared to AL (pdiet<0.0001). Taken together, these tests suggest eTRF results in males who experience glucose intolerance and insulin sensitivity whereas females are more resilient to glycemic changes after gestational eTRF. Given that we cannot explain glucose intolerance in males via reduced insulin sensitivity, we next evaluated insulin secretion.

After noticing a consistent trend in both cohorts of eTRF males developing glucose intolerance after HFHS diet exposure, we sought to explore cohort 2 more closely for insulin secretion defects, via an *in vivo* glucose stimulated insulin secretion (GSIS) assay (**Figure 3J**).Females had lower levels of insulin than males (psex<0.0001). There was a non-significant trend toward lower insulin levels in eTRF compared to AL offspring of both sexes (pdiet=0.071). Females had similar increases in insulin in response to glucose injection, 139% in AL versus 137% eTRF. Male AL offspring had a 48% increase in insulin whereas this was just an 18% increase for eTRF males. There was no interaction between sex and maternal restriction (psex:diet=0.064). Females have 94% greater fold-change insulin secretion in response to glucose challenge than male offspring (psex=0.0027) but there was no impact of maternal restriction on fold change secretion (p=0.85, **Figure 3K**). Male and female offspring of eTRF dams had lower baseline insulin values compared to AL dams, which we believe resulted in the similarity of fold change insulin secretion between maternal restriction groups. This study was not conclusive as it had a lower sample size and failed to reach statistical significance, but could indicate that insulin secretion is more impaired in eTRF offspring than in AL, especially after HFHS challenge in males*.*



Figure : **Body Composition, Food Intake, and Glycemic Response to High Fat, High Sucrose Diet Feeding in Adulthood**

**A)** Body weight in grams from PND 70-175 in males and females, averaged by age, maternal feeding regimen, and sex. **B)** Fat massin grams from PND 70-175 in males and females, averaged by age, maternal feeding regimen, and sex. **C)** Lean massin grams from PND 70-175 in males and females, averaged by age, maternal feeding regimen, and sex. **D)** High fat, high sucrose diet (HFHS) intake in kcals per mouse per day averaged by week, maternal feeding regimen, and sex. **E)** Insulin tolerance test (ITT) after 10 week of HFHS, averaged by age, maternal feeding regimen, sex, and time in minutes. **F)** Area under the curve (AUC) for insulin tolerance test, averaged by maternal feeding regimen, and sex. \* indicates, p-value <0.05 for diet in males. **G)** Glucose tolerance test (GTT) after 10 weeks of HFHS, averaged by maternal feeding regimen, sex and time in minutes. **H)** Area under the curve (AUC) for GTT after 10 weeks of HFHS, averaged by maternal feeding regimen and sex. \* indicates p-value <0.05 for effect of diet in males. **I)** Fasting blood glucose (FBG) after 10 weeks HFHS, averaged by maternal feeding regimen, and sex. **J)** Glucose stimulated insulin secretion (GSIS), averaged by maternal feeding regiment, sex, and time. \* indicates p-value <0.05 for effect of sex. Animals included in body composition, FBG, ITT, GTT, and GSIS: n=11 eTRF males, 16 AL males, 19 eTRF females, 17 AL females. Cages in food intake analysis: n=4 eTRF males, 5 AL males, 4 eTRF females, 5 AL females.

## Discussion

This study is the second to describe the long-term effects of gestational eTRF on offspring health and the first to describe their response to a high fat, high sucrose diet challenge. We find minimal effects associated with eTRF during gestation while male and female offspring are consuming a chow diet through early adulthood. However, after prolonged HFHS diet feeding, there are deleterious effects on glucose tolerance only in adult male progeny. Taken together, results from insulin and glucose tolerance testing, and exploratory GSIS after HFHS feeding strongly implicates differences in insulin secretion between eTRF males. However, the latter was preliminary and did not reach statistical significance. The other study of gestational (12-hour) TRF of chow diet in rats also found evidence of glucose intolerance and insulin sensitivity in the offspring of TRF dams, which is similar to the phenotype we note in male eTRF offspring after prolonged HFHS feeding (14). However, there are some differences compared to the current study. Most notably, they found impaired glucose stimulated insulin secretion in both male and female offspring who had not been exposed to high fat diet. These glycemic effects *in vivo* were apparent in female offspring, but were present in both male and female offspring *in vitro.* Furthermore, this group found further impairments in eTRF offspring *in vivo* when timed feeding was during the light cycle. The modest reduction of insulin at baseline during GSIS in eTRF offspring may contribute to the modest insulin sensitivity seen after HFHS feeding in the current study, and insulin sensitivity *in vivo* was evident in females in Prates and colleagues (14). There were reductions in insulin secretion in response to high glucose in male and female dark-cycle fed islets after gestational TRF, suggesting this may be a contributing mechanism for metabolic disruption in our model of gestational TRF.

Comparing the current study with other studies utilizing HFHS diets and TRF demonstrates some consistencies in glycemic outcomes. Fasting insulin can be lowered (27–30, 36), similar to our findings, and resulting HOMA-IR can be improved with TRF (29, 36, 37). Our finding that fasting blood glucose is unchanged in eTRF compared to AL exposed mice is consistent with other groups examining TRF with HFHS (27, 36, 37). Some differences in the current studies are not reflected in the literature, such as elevated food intake while on NCD in female offspring exposed to eTRF *in utero* is novel and was not seen in the other longitudinal analysis of offspring health following gestational TRF (14). Studies of adult mice pairing TRF and HFHS report reduced food intake (31, 38) or equivalent caloric intake when matched by diet (28–30, 39). This could indicate a compensatory response in the female offspring resulting from eTRF *in utero*. Interestingly, this did not result in differing body weight or composition, suggesting that this increased food intake is matched by decreased caloric extraction or increased energy expenditure in these mice.

The phenotype in male offspring from time-restricted feeding bears resemblance to animal models of mild intrauterine nutrient restriction, where glucose intolerance in resultant offspring can be a common phenotype. First described by Barker and colleagues, offspring who were deprived of nutrition *in utero* were more likely to develop chronic, nutrition-related disease in adulthood (40). Since that time, multiple animal models for gestational nutrient restriction were developed; maternal overnutrition during pregnancy, maternal caloric restriction, maternal protein restriction, and surgically induced placental insufficiency through late gestation uterine artery ligation. Undernutrition in pregnancy can often result in offspring development of glucose intolerance (41–43). The extent to which male-predominate phenotypes and female resilience to changes are difficult to deduce as many groups either study male offspring exclusively (43, 44) or analyze males and females together (42, 45). Male offspring who had placental insufficiency can develop glucose intolerance in adulthood (46, 47), so too can females (48, 49). Maternal overnutrition can also result in males with glucose intolerance (50, 51). Therefore, metabolic effects being limited in the current study to male offspring is consistent with much of the literature, as females appear to be less affected. Of note, these studies routinely find reductions in body weight as early as day 1 of postnatal life. This is inconsistent with the current study where we see no statistical reductions in body weight on either NCD or HFHS.

Although we did not evaluate insulin conclusively in the current study, glucose intolerance in nutrient restriction models has been found to co-occur with insulin-related abnormalities in the offspring, including lower insulin content in the pancreas (42), lower basal insulin levels (45), impaired insulin secretion (43, 49), increased pancreatic islet size (51), altered vascularity of islets (52), or reduced beta cell mass (53). These abnormalities are also accompanied by abnormal glucose tolerance in adulthood (41, 51). However, in the present study we find modest improvement in male insulin sensitivity in adulthood in male offspring exposed to gestational eTRF. This finding is similar to the previous study where females exposed to gestational TRF had greater rates of glucose disappearance during insulin tolerance testing (14). We believe that the insulin sensitivity during high fat, high sucrose diet feeding in eTRF males is related to having lower basal levels of insulin compared to AL males in our model. This could result in peripheral tissues being more sensitive to insulin action despite an apparent insulin secretion impairment at the level of the pancreas.

In contrast to the previous study and some models of nutrient restriction in pregnancy, we did not observe major metabolic differences between restricted and unrestricted offspring until a HFHS diet challenge occurred in adulthood. This could suggest that gestational eTRF may be relatively safe to practice in the context of a healthful diet or absent a second challenge. However, it also suggests that in the context of unhealthy diet patterns, adult offspring may be ill-equipped to adapt to high-calorie food environments, leading to metabolic dysfunction. These studies differ both in the age of onset and duration of food restriction that are required to initiate glucose intolerance in offspring of TRF dams which also may explain these differences. Modeling of this dietary strategy remains incomplete, so translation to human clinical populations is not possible at this time. The similarity of the present study to those using diverse gestational stressors suggests that restriction of the total time pregnant dams is a novel dietary component that can have lasting impact on the spent eating in metabolic health of offspring and recommends further research on this novel component in the diet as a modulator of maternal and child metabolic health outcomes.

Although we have not investigated offspring pancreatic tissues, we hypothesize that alterations in the development of the pancreas may underlie the susceptibility of males for glucose intolerance and modest insulin sensitivity in eTRF offspring after HFHS feeding. There is recent evidence that this could be at least partially related to pancreas response to glucose, as *in vitro* and *in vivo* assessment of glycemic health were in line with our current findings, though more robust than the GSIS completed in the current study (14). Intrinsic changes in islet function are also possible. Studies done in adult male animals undergoing TRF with chronodisruption have also found that time-restricting food access reduced insulin production with secretion most affected (enhanced compared to controls) and found no effect of insulin tolerance (54). This is confirmed by one study of early post-natal exposure to TRF, which found that adolescent males who were fed TRF the first 4 weeks after weaning developed smaller islets of Langerhans and higher blood glucose compared to those fed AL (39). Therefore, future studies of gestational or developmental eTRF should examine islet size, pancreatic beta cell mass, and insulin secretion to investigate the mechanism of offspring glucose intolerance more conclusively.

This study and the conclusions to be made from it have some limitations. First, the model of gestational eTRF may have resulted in differences in maternal behaviors that were not noted by the study team, and therefore could play a part in the effects seen in the offspring. Second, although we see a robust effect on glucose intolerance, we were not powered to conclusively establish lower insulin secretion in male eTRF offspring in adulthood, and have not yet evaluated islet size or beta cell mass to determine the mechanisms driving the worsening of glucose tolerance in adulthood in male mice or the resilience of female mice. We hope that future studies will describe these effects in larger samples and with higher resolution so that more in-depth conclusions can be drawn.

There are many strengths to this study. Among them are the use of a preclinical model which facilitates consistency when compared to existing literature and allows for careful control of diet, genetics, and environment throughout gestation, which would be impossible at this point in a human trial. Further strengths include the long follow up period for a gestational exposure, controlling for the effect of litter size, repeated measurement of body composition, and food intake measurements over the life course in the resultant offspring. Finally, the inclusion of both male and female offspring in the study, as many metabolic assessments of TRF either focus exclusively on the effects of the regimen in males (29, 30) or female mice (27, 28) is a strength. Finally, our model used healthy non-obese dams and our results cannot be extended to effects of eTRF in the context of metabolic syndrome, diabetes, or obesity during pregnancy.

## Conclusion

Offspring who are exposed to eTRF of NCD *in utero* have similar body composition, glucose tolerance, and insulin tolerance in early adulthood in both males and females. Gestational eTRF resulted in male impairments in glucose tolerance in adulthood only after chronic HFHS feeding, whereas females appeared resilient to and did not develop differences. This occurs without increase in body weight, fat mass, or food intake compared to age matched AL males. More research is warranted to understand the mechanisms that underlie this novel phenotype.

# Appendices

Be sure to visit [the ScholarSpace guide](http://guides.lib.umich.edu/word2010) to learn more about how to format your appendices.

# Bibliography

1. **Lee C**, **Etchegaray J-P**, **Cagampang FRA**, **Loudon ASI**, **Reppert SM**. Posttranslational Mechanisms Regulate the Mammalian Circadian Clock. *Cell* 107: 855–867, 2001. doi: 10.1016/S0092-8674(01)00610-9.

2. **Panda S**. Circadian physiology of metabolism. *Science* 354: 1008–1015, 2016. doi: 10.1126/science.aah4967.

3. **Takahashi JS**. Transcriptional architecture of the mammalian circadian clock. *Nat Rev Genet* 18: 164–179, 2017. doi: 10.1038/nrg.2016.150.

4. **Pickel L**, **Sung H-K**. Feeding Rhythms and the Circadian Regulation of Metabolism [Online]. *Frontiers in Nutrition* 7, 2020. https://www.frontiersin.org/article/10.3389/fnut.2020.00039 [30 Jun. 2022].

5. **Manoogian ENC**, **Panda S**. Circadian rhythms, time-restricted feeding, and healthy aging. *Ageing Research Reviews* 39: 59–67, 2017. doi: 10.1016/j.arr.2016.12.006.

6. **International Food Information Council**. 2020 Food & Health Survey [Online]. https://foodinsight.org/2020-food-and-health-survey/.

7. **Loy SL**, **Chan JKY**, **Wee PH**, **Colega MT**, **Cheung YB**, **Godfrey KM**, **Kwek K**, **Saw SM**, **Chong Y-S**, **Natarajan P**, **Müller-Riemenschneider F**, **Lek N**, **Chong MF-F**, **Yap F**. Maternal Circadian Eating Time and Frequency Are Associated with Blood Glucose Concentrations during Pregnancy. *J Nutr* 147: 70–77, 2017. doi: 10.3945/jn.116.239392.

8. **Flanagan EW**, **Kebbe M**, **Sparks JR**, **Redman LM**. Assessment of Eating Behaviors and Perceptions of Time-Restricted Eating During Pregnancy. *The Journal of Nutrition* 152: 475–483, 2022. doi: 10.1093/jn/nxab397.

9. **Glazier JD**, **Hayes DJL**, **Hussain S**, **D’Souza SW**, **Whitcombe J**, **Heazell AEP**, **Ashton N**. The effect of Ramadan fasting during pregnancy on perinatal outcomes: a systematic review and meta-analysis. *BMC Pregnancy Childbirth* 18, 2018. doi: 10.1186/s12884-018-2048-y.

10. **Oosterwijk VNL**, **Molenaar JM**, **van Bilsen LA**, **Kiefte-de Jong JC**. Ramadan Fasting during Pregnancy and Health Outcomes in Offspring: A Systematic Review. *Nutrients* 13: 3450, 2021. doi: 10.3390/nu13103450.

11. **Ali AM**, **Kunugi H**. Intermittent Fasting, Dietary Modifications, and Exercise for the Control of Gestational Diabetes and Maternal Mood Dysregulation: A Review and a Case Report. *Int J Environ Res Public Health* 17: 9379, 2020. doi: 10.3390/ijerph17249379.

12. **Upadhyay A**, **Sinha RA**, **Kumar A**, **Godbole MM**. Time-restricted feeding ameliorates maternal high-fat diet-induced fetal lung injury. *Experimental and Molecular Pathology* 114: 104413, 2020. doi: 10.1016/j.yexmp.2020.104413.

13. **Upadhyay A**, **Anjum B**, **Godbole NM**, **Rajak S**, **Shukla P**, **Tiwari S**, **Sinha RA**, **Godbole MM**. Time-restricted feeding reduces high-fat diet associated placental inflammation and limits adverse effects on fetal organ development. *Biochemical and Biophysical Research Communications* 514: 415–421, 2019. doi: 10.1016/j.bbrc.2019.04.154.

14. **Prates KV**, **Pavanello A**, **Gongora AB**, **Moreira VM**, **de Moraes AMP**, **Rigo KP**, **Vieira E**, **Mathias PC de F**. Time-restricted feeding during embryonic development leads to metabolic dysfunction in adult rat offspring. .

15. **Cienfuegos S**, **Gabel K**, **Kalam F**, **Ezpeleta M**, **Wiseman E**, **Pavlou V**, **Lin S**, **Oliveira ML**, **Varady KA**. Effects of 4- and 6-h Time-Restricted Feeding on Weight and Cardiometabolic Health: A Randomized Controlled Trial in Adults with Obesity. *Cell Metabolism* 32: 366-378.e3, 2020. doi: 10.1016/j.cmet.2020.06.018.

16. **Gabel K**, **Hoddy KK**, **Haggerty N**, **Song J**, **Kroeger CM**, **Trepanowski JF**, **Panda S**, **Varady KA**. Effects of 8-hour time restricted feeding on body weight and metabolic disease risk factors in obese adults: A pilot study. *Nutr Healthy Aging* 4: 345–353, 2018. doi: 10.3233/NHA-170036.

17. **Gill S**, **Panda S**. A smartphone app reveals erratic diurnal eating patterns in humans that can be modulated for health benefits. *Cell Metab* 22: 789–798, 2015. doi: 10.1016/j.cmet.2015.09.005.

18. **Moro T**, **Tinsley G**, **Bianco A**, **Marcolin G**, **Pacelli QF**, **Battaglia G**, **Palma A**, **Gentil P**, **Neri M**, **Paoli A**. Effects of eight weeks of time-restricted feeding (16/8) on basal metabolism, maximal strength, body composition, inflammation, and cardiovascular risk factors in resistance-trained males. *J Transl Med* 14: 290, 2016. doi: 10.1186/s12967-016-1044-0.

19. **Antoni R**, **Robertson TM**, **Robertson MD**, **Johnston JD**. A pilot feasibility study exploring the effects of a moderate time-restricted feeding intervention on energy intake, adiposity and metabolic physiology in free-living human subjects. *Journal of Nutritional Science* 7, 2018. doi: 10.1017/jns.2018.13.

20. **Lowe DA**, **Wu N**, **Rohdin-Bibby L**, **Moore AH**, **Kelly N**, **Liu YE**, **Philip E**, **Vittinghoff E**, **Heymsfield SB**, **Olgin JE**, **Shepherd JA**, **Weiss EJ**. Effects of Time-Restricted Eating on Weight Loss and Other Metabolic Parameters in Women and Men With Overweight and Obesity: The TREAT Randomized Clinical Trial. .

21. **Sutton EF**, **Beyl R**, **Early KS**, **Cefalu WT**, **Ravussin E**, **Peterson CM**. Early Time-Restricted Feeding Improves Insulin Sensitivity, Blood Pressure, and Oxidative Stress Even without Weight Loss in Men with Prediabetes. *Cell Metabolism* 27: 1212-1221.e3, 2018. doi: 10.1016/j.cmet.2018.04.010.

22. **Hutchison AT**, **Regmi P**, **Manoogian ENC**, **Fleischer JG**, **Wittert GA**, **Panda S**, **Heilbronn LK**. Time-Restricted Feeding Improves Glucose Tolerance in Men at Risk for Type 2 Diabetes: A Randomized Crossover Trial. *Obesity* 27: 724–732, 2019. doi: 10.1002/oby.22449.

23. **Jamshed H**, **Beyl RA**, **Della Manna DL**, **Yang ES**, **Ravussin E**, **Peterson CM**. Early Time-Restricted Feeding Improves 24-Hour Glucose Levels and Affects Markers of the Circadian Clock, Aging, and Autophagy in Humans. *Nutrients* 11: 1234, 2019. doi: 10.3390/nu11061234.

24. **Wilkinson MJ**, **Manoogian ENC**, **Zadourian A**, **Lo H**, **Fakhouri S**, **Shoghi A**, **Wang X**, **Fleischer JG**, **Navlakha S**, **Panda S**, **Taub PR**. Ten-Hour Time-Restricted Eating Reduces Weight, Blood Pressure, and Atherogenic Lipids in Patients with Metabolic Syndrome. *Cell Metab* 31: 92-104.e5, 2020. doi: 10.1016/j.cmet.2019.11.004.

25. **Boucsein A**, **Rizwan MZ**, **Tups A**. Hypothalamic leptin sensitivity and health benefits of time-restricted feeding are dependent on the time of day in male mice. *FASEB J* 33: 12175–12187, 2019. doi: 10.1096/fj.201901004R.

26. **Chaix A**, **Zarrinpar A**, **Miu P**, **Panda S**. Time-restricted feeding is a preventative and therapeutic intervention against diverse nutritional challenges. *Cell Metab* 20: 991–1005, 2014. doi: 10.1016/j.cmet.2014.11.001.

27. **Chung H**, **Chou W**, **Sears DD**, **Patterson RE**, **Webster NJG**, **Ellies LG**. Time-restricted feeding improves insulin resistance and hepatic steatosis in a mouse model of postmenopausal obesity. *Metabolism* 65: 1743–1754, 2016. doi: 10.1016/j.metabol.2016.09.006.

28. **Das M**, **Ellies LG**, **Kumar D**, **Sauceda C**, **Oberg A**, **Gross E**, **Mandt T**, **Newton IG**, **Kaur M**, **Sears DD**, **Webster NJG**. Time-restricted feeding normalizes hyperinsulinemia to inhibit breast cancer in obese postmenopausal mouse models. *Nat Commun* 12: 565, 2021. doi: 10.1038/s41467-020-20743-7.

29. **Hatori M**, **Vollmers C**, **Zarrinpar A**, **DiTacchio L**, **Bushong EA**, **Gill S**, **Leblanc M**, **Chaix A**, **Joens M**, **Fitzpatrick JAJ**, **Ellisman MH**, **Panda S**. Time-Restricted Feeding without Reducing Caloric Intake Prevents Metabolic Diseases in Mice Fed a High-Fat Diet. *Cell Metabolism* 15: 848–860, 2012. doi: 10.1016/j.cmet.2012.04.019.

30. **Sherman H**, **Genzer Y**, **Cohen R**, **Chapnik N**, **Madar Z**, **Froy O**. Timed high-fat diet resets circadian metabolism and prevents obesity. *FASEB J* 26: 3493–3502, 2012. doi: 10.1096/fj.12-208868.

31. **She Y**, **Sun J**, **Hou P**, **Fang P**, **Zhang Z**. Time-restricted feeding attenuates gluconeogenic activity through inhibition of PGC-1α expression and activity. *Physiology & Behavior* 231: 113313, 2021. doi: 10.1016/j.physbeh.2021.113313.

32. **R Core Team**. R: A Language and Environment for Statistical Computing [Online]. R Foundation for Statistical Computing: 2021. https://www.R-project.org/.

33. **Bates D**, **Mächler M**, **Bolker B**, **Walker S**. Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software* 67: 1–48, 2015. doi: 10.18637/jss.v067.i01.

34. **Ladyman SR**, **Carter KM**, **Grattan DR**. Energy homeostasis and running wheel activity during pregnancy in the mouse. *Physiology & Behavior* 194: 83–94, 2018. doi: 10.1016/j.physbeh.2018.05.002.

35. **Nutrition NRC (US) S on LA**. Nutrient Requirements of the Mouse [Online]. National Academies Press (US). https://www.ncbi.nlm.nih.gov/books/NBK231918/ [27 Jul. 2022].

36. **Woodie LN**, **Luo Y**, **Wayne MJ**, **Graff EC**, **Ahmed B**, **O’Neill AM**, **Greene MW**. Restricted feeding for 9h in the active period partially abrogates the detrimental metabolic effects of a Western diet with liquid sugar consumption in mice. *Metabolism* 82: 1–13, 2018. doi: 10.1016/j.metabol.2017.12.004.

37. **Chaix A**, **Lin T**, **Le HD**, **Chang MW**, **Panda S**. Time-Restricted Feeding Prevents Obesity and Metabolic Syndrome in Mice Lacking a Circadian Clock. *Cell Metabolism* 29: 303-319.e4, 2019. doi: 10.1016/j.cmet.2018.08.004.

38. **García-Gaytán AC**, **Miranda-Anaya M**, **Turrubiate I**, **López-De Portugal L**, **Bocanegra-Botello GN**, **López-Islas A**, **Díaz-Muñoz M**, **Méndez I**. Synchronization of the circadian clock by time-restricted feeding with progressive increasing calorie intake. Resemblances and differences regarding a sustained hypocaloric restriction. *Sci Rep* 10, 2020. doi: 10.1038/s41598-020-66538-0.

39. **Hu D**, **Mao Y**, **Xu G**, **Liao W**, **Ren J**, **Yang H**, **Yang J**, **Sun L**, **Chen H**, **Wang W**, **Wang Y**, **Sang X**, **Lu X**, **Zhang H**, **Zhong S**. Time-restricted feeding causes irreversible metabolic disorders and gut microbiota shift in pediatric mice. *Pediatr Res* 85: 518–526, 2019. doi: 10.1038/s41390-018-0156-z.

40. **Barker DJ**, **Gluckman PD**, **Godfrey KM**, **Harding JE**, **Owens JA**, **Robinson JS**. Fetal nutrition and cardiovascular disease in adult life. *Lancet* 341: 938–941, 1993. doi: 10.1016/0140-6736(93)91224-a.

41. **Alejandro EU**, **Jo S**, **Akhaphong B**, **Llacer PR**, **Gianchandani M**, **Gregg B**, **Parlee SD**, **MacDougald OA**, **Bernal-Mizrachi E**. Maternal low-protein diet on the last week of pregnancy contributes to insulin resistance and β-cell dysfunction in the mouse offspring. *Am J Physiol Regul Integr Comp Physiol* 319: R485–R496, 2020. doi: 10.1152/ajpregu.00284.2019.

42. **Shahkhalili Y**, **Moulin J**, **Zbinden I**, **Aprikian O**, **Macé K**. Comparison of two models of intrauterine growth restriction for early catch-up growth and later development of glucose intolerance and obesity in rats. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology* 298: R141–R146, 2010. doi: 10.1152/ajpregu.00128.2009.

43. **Yuan Q**, **Chen L**, **Liu C**, **Xu K**, **Mao X**, **Liu C**. Postnatal Pancreatic Islet β Cell Function and Insulin Sensitivity at Different Stages of Lifetime in Rats Born with Intrauterine Growth Retardation. *PLOS ONE* 6: e25167, 2011. doi: 10.1371/journal.pone.0025167.

44. **Radford BN**, **Han VKM**. Offspring from maternal nutrient restriction in mice show variations in adult glucose metabolism similar to human fetal growth restriction. *Journal of Developmental Origins of Health and Disease* 10: 469–478, 2019. doi: 10.1017/S2040174418000983.

45. **Wang J**, **Cao M**, **Zhuo Y**, **Che L**, **Fang Z**, **Xu S**, **Lin Y**, **Feng B**, **Wu D**. Catch-up growth following food restriction exacerbates adulthood glucose intolerance in pigs exposed to intrauterine undernutrition. *Nutrition* 32: 1275–1284, 2016. doi: 10.1016/j.nut.2016.03.010.

46. **Intapad S**, **Dasinger JH**, **Fahling JM**, **Backstrom MA**, **Alexander BT**. Testosterone is protective against impaired glucose metabolism in male intrauterine growth-restricted offspring. *PLOS ONE* 12: e0187843, 2017. doi: 10.1371/journal.pone.0187843.

47. **Intapad S**, **Dasinger JH**, **Johnson JM**, **Brown AD**, **Ojeda NB**, **Alexander BT**. Male and female intrauterine growth-restricted offspring differ in blood pressure, renal function, and glucose homeostasis responses to a post-natal diet high in fat and sugar. *Hypertension* 73: 620–629, 2019. doi: 10.1161/HYPERTENSIONAHA.118.12134.

48. **Jahandideh F**, **Bourque SL**, **Armstrong EA**, **Cherak SJ**, **Panahi S**, **Macala KF**, **Davidge ST**, **Yager JY**. Late-pregnancy uterine artery ligation increases susceptibility to postnatal Western diet-induced fat accumulation in adult female offspring. *Sci Rep* 10: 6926, 2020. doi: 10.1038/s41598-020-63392-y.

49. **Jansson T**, **Lambert GW**. Effect of intrauterine growth restriction on blood pressure, glucose tolerance and sympathetic nervous system activity in the rat at 3–4 months of age. *Journal of Hypertension* 17: 1239–1248, 1999.

50. **Zhang Q**, **Xiao X**, **Zheng J**, **Li M**, **Yu M**, **Ping F**, **Wang T**, **Wang X**. A Maternal High-Fat Diet Induces DNA Methylation Changes That Contribute to Glucose Intolerance in Offspring. *Front Endocrinol (Lausanne)* 10: 871, 2019. doi: 10.3389/fendo.2019.00871.

51. **Zheng J**, **Zhang L**, **Wang Z**, **Zhang J**. Maternal high-fat diet regulates glucose metabolism and pancreatic β cell phenotype in mouse offspring at weaning. *PeerJ* 8: e9407, 2020. doi: 10.7717/peerj.9407.

52. **Boehmer BH**, **Limesand SW**, **Rozance PJ**. The impact of IUGR on pancreatic islet development and β-cell function. *J Endocrinol* 235: R63–R76, 2017. doi: 10.1530/JOE-17-0076.

53. **Simmons RA**, **Templeton LJ**, **Gertz SJ**. Intrauterine Growth Retardation Leads to the Development of Type 2 Diabetes in the Rat. *Diabetes* 50: 2279–2286, 2001. doi: 10.2337/diabetes.50.10.2279.

54. **Brown MR**, **Sen SK**, **Mazzone A**, **Her TK**, **Xiong Y**, **Lee J-H**, **Javeed N**, **Colwell CS**, **Rakshit K**, **LeBrasseur NK**, **Gaspar-Maia A**, **Ordog T**, **Matveyenko AV**. Time-restricted feeding prevents deleterious metabolic effects of circadian disruption through epigenetic control of β cell function. *Sci Adv* 7: eabg6856, 2021. doi: 10.1126/sciadv.abg6856.