**Model Organism Aim 2: Determine the effects of gestational manipulation of the feeding window on offspring health at birth, during growth and development, and in response to Western dietary challenge.**

2.1 Body Weight, Survival, Gestational age

2.2-> growth and development + insulin TT

* Pubertal onset/DEVELOPMENTAL WINDOW

2.3 HFD

2.4 metabolic syndrome

Liver fat

Tgemia

GTT  
ITT

insulinemia

2.5 Mechanisms?

GINTOL INSUL SENS -> GSIS

## Background:

### Childhood origins of metabolic disease

* Introduction of DOHaD
  + Dutch hunger winter
  + Studies of nutrient restriction in gestation in animal models have demonstrated that caloric restriction increases incidence of low birthweight, and may initiate unhealthful catch up growth upon weaning, resulting in excess body weight, body fat, and leptin resistance upon reaching adulthood(Ross & Desai, 2005).
  + Organogenesis/2-hit hypothesis

### Early life exposure to time restricted feeding

Early life is characterized by rapid rates of growth and differentiation and furthermore is a critical period for programming propensity for dysmetabolism. There is substantial evidence that gestation is a critical time for future offspring health. Studies in humans have demonstrated that exposure to food shortage/famine can Further evidence has demonstrated that the immediate post-natal life and time preceding adulthood are also crucial in determining risk of ill health in adult life. The largest literature of maternal time-restricted feeding in pregnancy exists in women fasting in observance of Ramadan during their pregnancies. These studies show that gestational age is often similar between those who fasted and those who did not fast during pregnancy. Furthermore, there may be a greater incidence in low birth weight babies, especially if the Ramadan fasting took place in the first trimester of pregnancy. However, it is my belief that Ramadan fasting is not a good proxy for TRF during gestation, as it may better model of food entrained chronodisruption during gestation, which has been shown by Salazar and colleagues to be detrimental to disrupt glucocorticoid stress signaling in rat fetuses, thereby altering their propensity to develop metabolic disease(Salazar et al., 2018).

#### Early Post-natal Time-Restricted Feeding

In the field of DOHad, the early parts of life extend beyond the gestation period and extend into the early post-natal life. Time-restricted feeding has been evaluated in the early postnatal period in one study, in hope it would mitigate the development of obesity later in life. This study began 8-hour, dark cycle TRF immediately after weaning and kept pups on this schedule for 4 weeks. After 4 weeks, they were switched to AL feeding. Instead of the typical protective effects often seen in TRF in adult populations, harmful metabolic effects were noted. Among them are hyperglycemia, reduced size and area of pancreatic islets, reduced insulin production, increased fatty liver, reduced immune competency, and delayed pubertal maturation(Hu et al., 2019). This suggests that there are effects of TRF in the development period. However, the early post-natal life is distinct from the gestational period; as it is the time for behavior, brain, and development, as opposed to the main time of tissue accretion, organogenesis and \_\_\_ that gestation is(CITE). Therefore, post-natal TRF effects are unlikely to be the same as those during gestation.

#### Gestational Time Restricted Feeding

One work has been completed in gestational eTRF. This focused on HFD-TRF feeding in comparison to HFD-AL feeding. This paper focused on in utero and maternal general habitus, and failed to

Upadhyay and colleagues demonstrated the TRF of HFD could be protective compared to AL HFD feeding on fetal development, with a normalization of placetal:fetal ratio, lower liver TG, and improved lung maturity in TRF fed fetuses at E18.5. This suggests that TRF is able to abrogate the effects of high fat diet feeding in utero. It would be worthwhile to see the effects of TRF-NCD. However, the post-natal period, including birth indices, survival, growth, and metabolic health were not evaluated in this study, therefore eTRF effects on the offspring have yet to be characterized in the literature.

## Specific aim 2.1 Will dam eTRF during gestation affect pup birth indices and survival?

What do we know

What is missing

What we want to do

What we expect to see

The impact it will have

The effects of intermittent fasting on birthweight, gestational age, and offspring survival have not been thoroughly evaluated.

Aim 2.1.1Body Weight

Birthweight is an important indicator of child health that is associated with infant mortality, and even more recently found to correlate to adult obesity risk (Law, 2002). The effect intermittent fasting during pregnancy has on birth weight has not been examined in either animal or human studies. That being said, the closest proxy to intermittent fasting in pregnant human populations is that fasting that takes place during the month of Ramadan. During this time, consumption of both food and liquids is restricted to sun down. The effects of Ramadan fasting during pregnancy on offspring early health outcomes are inconsistent. Some studies find exposure to fasting during Ramadan during pregnancy has no effect on child birthweight (Awwad et al., 2012; Hizli et al., 2012; Savitri et al., 2018), while still others note increased risk for low birthweight (Daley et al., 2017; *Ramadan during pregnancy and birth weight of newborns*, n.d.; Savitri et al., 2014; Ziaee et al., 2010), especially if exposure to fasting was in early gestation.

Other studies of nutrient restriction during gestation have been done and it is often seen that birthweights in nutritionally restricted pregnancies are more likely to be lower than normally fed pregnancies. It is also seen that timing of restriction may play a particularly prominent role in determining risk of low birth weight. Fetuses exposed to the Dutch hunger winter early during gestation had lower birth weights, but those who were exposed during late gestation had normal birthweights (Schulz, 2010). Total nutrient restriction and daytime fasting are not good proxies for IF, as they either reduce total number of calories and crucial macronutrients or introduce a disruption to the natural circadian cycle of eating and sleeping. The only study to date of gestational TRF was conducted by Upadhyay and colleagues and demonstrated that HFD-TRF feeding during pregnancy generated produced pups with comparable birth weights to AL fed controls (Upadhyay et al., 2019). This dietary strategy also corrected large birthweight traditionally seen in HFD feeding (Upadhyay et al., 2019). Therefore, I anticipate that birth weight of pups will be similar in both eTRF and AL fed dams. To determine the effect of maternal dietary feeding strategy on pup birth weight, each pup’s weight will be taken immediately after delivery (PND 0.5). Pup birth weight will be averaged by litter and then by dam to present an average pup weight. Preliminary cohort data demonstrates that average birthweight per pup does not differ between maternal feeding groups (p = 0.7).

Aim 2.1.2 Gestational age

Another crucial measure of early life health is gestational age. Gestational age, failing to reach term before birth (pre-term birth), has been linked to worsened early child health (Boyle et al., 2012). The effect of Ramadan fasting in pregnancy on gestational age is more consistent in the literature, with studies finding no effect of maternal fasting on gestational age (Awwad et al., 2012; Daley et al., 2017; Hizli et al., 2012; Savitri et al., 2014). No study in animals has been done to date. To assess gestational age, we will count the number of days between appearance of copulatory plug and birth. I predict that gestational age will not differ between maternal treatment groups. The impact of this study will be that we will have the first evidence for iso-caloric time restricted feeding in animals and its influence on risk for pre-term birth.

Aim 2.1.3 Survival

One study of moderate caloric restriction (85% of needs) during early gestations in ewes found no differences in birthweight or body weight in either fetuses or in lambs, but did see increases in lamb’s adrenal glad weights- a change that was not present in the fetuses from similarly restricted ewes(Hawkins et al., 2000).

* Canonical studies of food restriction report that with caloric restriction during gestation, there is \_\_\_\_ effect on survival of the pups(CITE).
* Some studies use food deprivation as a means to induce stress in maternal animals. This may be enough to impact survival of the pups.

Sex differences may exist in the survivorship of offspring. Work done in dairy cows has demonstrated that restrictive feeding practices initiated before mating resulted in smaller calves, and fewer female calves surviving compared to AL fed controls (Vinsky, Novak, Dixon, Dyck, & Foxcroft, 2006). However, the majority of animal models find that TRF rarely induces caloric deficit when compared to AL fed controls (CITE ALL THESE). In order to assess survival of the pups, offspring will be counted on PND 0.5 and sexed as soon as possible. This number will be tracked daily until selective reduction at PND 3.5. The sex-specific effects of eTRF on pup survival was not something we evaluated in the first cohort, but we will in the future be sexing and recording weights of all fetuses before culling to even litters. This will better enable us to detect any sex-specific differences in early post-natal survival or in birth numbers.

## Specific aim 2.2 Will gestational exposure to eTRF alter growth and development of the offspring?

Growth encompasses many factors including the trajectory of body composition, the propensity for food intake and energy expenditure, and of sexual maturation.

Aim 2.2.1 Body weight, food intake

It is well documented that maternal diet during gestation can alter offspring body composition. The ability of an animal to gain weight and length is correlated to its propensity for disease (CITE). There is potential for catch-up growth. This would look like \_\_\_\_\_.

Aim 2.2.2 Metabolic health in adolescence

Adolesence is a critical period of development characterized by rapid growth, sexual development, and concordance of many health indices with the adult risk profiles they carry. Therefore, early adulthood/adolescence is a critical time to assess metabolic health. In order to assess metabolic health, this study suggests to assess the same aspect that was shown in the previous generation, insulin sensitivity. To assess this, we will conduct an insulin tolerance test. I

Aim 2.2.3 Sexual development and maturation

Less significant induction of the integrated stress response suggests that he in utero environment is not one that is inhospitable to fetuses, but may be one that is slightly stressed, as the ISR was moderately upregulated compared to NCD-AL feeding (Upadhyay et al., 2019).

* BC, weight, food intake
* Limiting litters

One existing study to evaluate TRF in developing animals discovered that TRF in the post weaning life, even when followed by 4 weeks of AL feeding, elicited severe metabolic dysfunction in mice (Hu et al., 2019). This was not improved by continued TRF feeding and manifested despite being fed a chow diet. The TRF animals demonstrated hyperglycemia, impaired liver function, reduced immune response, altered gut microbiome, and delayed sexual maturation (Hu et al., 2019).

## Specific aim 2.3 Will gestational exposure to eTRF confer metabolic benefit when challenged with a high fat diet?

Initiation of high fat diet feeding is consistent in the literature in creating the appropriate milieu to generate the metabolic syndrome in mice. Among the characteristics of the metabolic syndrome, are many indicidual organ shifts away from halthy tissue with good function. Such as increases in liver fat, leading to non-alcoholic fatty liver disease (NAFLD), Increases of adipose tissue, increases in blood lipids, insulin insensitivity, glucose intolerance, and higher insulin concentrations that healthy controls.

NAFLD

* Some animal studies of TRF have demonstrated effects on indices of NAFLD. In general,

Triglyceridemia

Liver Fat

ITT

GTT

Insulinemia

If D then why

* I hypothesize that eTRF animals will have resistance to DIO because \_\_\_\_. To test this, at adulthood (70 days of age) all offspring will be switched to a 45% HFD. This diet treatment will remain for 10-12 weeks. Weekly measurements of body weight, fat mass, lean mass, and food intake will be assessed.
* The hypothesis is that in response to a HFD, TRF exposed mice will be more resistant to diet induced obesity, manifesting as a lower body fat percentage. It is also entirely possible that HFD will be poorly received as it does not match the utero environment, making TRF exposed mice more likely to be hyperglycemic or fat.
* WHY WOULD THEY BE RESISTANT TO A HFD?
  + It could be that because they had no exposure to this type of feeding/nutrient levels in the womb, that they are particularly susceptible to HFD-induced metabolic disease.

## Specific aim 2.4 Will gestational exposure to eTRF improve insulin sensitivity and glycemia of offspring?

The many studies in humans and in animals of TRF demonstrate a consistent propensity for improvement in insulin and glucose homeostasis. Notably, three human studies noticed a reduction in glycemia (Halberg et al., 2005; Jamshed et al., 2019; Moro et al., 2016); # of animal studies (Liu et al., 2019), and 3 human studies demonstrated reductions in insulinemia (Jamshed et al., 2019; Moro et al., 2016; Sutton et al., 2018)and 3 in animal studies(Liu et al., 2019; Sherman et al., 2012; Woodie et al., 2018). Evidence in animals is more consistent for reductions in insulin with no differences seen in glycemia. For this reason, I expect that offspring born to dams fed eTRF will be more insulin sensitive but will have similar glucose levels as AL offspring. However, reduced insulin production, as is often seen in TRF papers, concomitant with the process of organogenesis of the metabolically active organs (pancreas, liver).

One model of maternal nutrient restriction that is often used in DOHaD is a low-protein diet, as it is know to cause IUGR and alter offspring health (CITE). One such study found that both blood glucose and insulin secretion are elevated in adult rats whose mothers were protein restricted compared to protein-replete fed dams(Hales, Desai, Ozanne, & Crowther, 1996). Because insulin does not precipitously affect the fetus and is prevented from entering fetal circulation (Widness, Goldman, Susa, Oh, & Schwartz, 1983), it is unlikely that insulin signaling affects the fetus *in utero.* Therefore the transfer of glycemic health from mother to offspring may be more related to glycemia that can cross the placenta and enter fetal circulation. Furthermore, this may be mediated by Incretins, one such study found that in offspring whose mothers were diabetic during gestation demonstrated lower start GLP 1 and reduced GLP 1 secretion as well as a more profound increase in glucagon response to an OGTT(Kelstrup et al., 2015). This could mean that offspring of dams who are more insulin sensitive may see the opposite effect, a glucose sensitization. In fact, GLP-1 is known to modulate adaptations of pancreatic beta cells to pregnancy (READ BEFORE YOU CITE AND CAN IT EXERT EFFECTS IF IT DOESN”T CROSS PLACENTA/DOES IT?).

* Think about hormones/signals that are increased by fasting and look into the periods of organogenesis---this has to have been done before.
* ITT at NCD/HFD why not GTT
* Why, cond/ obesity
* Taking blood and tissues
  + fasted blood – insulin/glucose/gut signaling peptides
  + Liver
  + iWat
  + Gwat
  + Quad

Specific aim 2.5 Mechanisms driving phenotype

Mechanisms evaluated

Maternal insulinemia->beta cell proliferation in offspring

GLP1

*Potential pitfalls and alternative approaches*

One of the most obvious concerns with a restrictive dietary intake for the gestational period is the development of intrauterine growth restriction (IUGR). One measure used in animal studies to determine if IUGR secondary to poor placentation has occurred is to measure the late term fetus to placenta ratio (FPR) CITE. Based on dams following this strategy in a previous study, pups at day E 18.5 who resulted from dams who were TRF HFD, there was a resolution in the placental insufficiency seen with AL HFD feeding; however, it is important to note that FPR was not quite the same as AL-NCD fed controls (Upadhyay et al., 2019), it may be that IUGR is not likely with TRF as long as caloric needs are met in the restricted feeding period. Furthermore, it was seen that lung development in the TRF-HFD group was more advanced than in AL-HFD group pups, meaning that development was more complete, despite a moderate phenotype of partially altered FPR. If that measure isn’t appropriate, we could also make it more translatable by comparing birth weights of pups to other growth curves generated in the C57/B6J mouse (Dilworth et al., 2011).

Poor lactation/maternal attentiveness

One unintentional consequence of altering maternal feeding strategy could be that stress would affect maternal attentiveness or lactation. These effects are difficult to gauge, as most studies that evaluate stressors from diet or the psychosocial atmosphere also continue that stressor during lactation. This study does not plan to do so, in order to be able to tell if an offspring phenotype that is generated is directly related to the gestational exposure alone. One such way to determine in lactation is affected, is to determine maternal milk production in relation to fetal suckling (Boston, Bleck, Conroy, Wheeler, & Miller, 2001). This has been done before by our group and was able to detect lower weight gained from nursing in TSC-KO pups (Unpublished data, Noura El Habbal, 2019) .

Sex diff

One possible pitfall could be that variation in the early post-natal period could have sex-specific effects for birth weight or survival. Sexual dimorphism, as early as *in utero* is known to exist in mouse species. This has been contributed to differences such as placental differences between male and female fetuses. Furthermore effects of maternal undernutrition has also demonstrated sex-specific phenotypes (example)(Gabory, Roseboom, Moore, Moore, & Junien, 2013). If this is the case, we can account for this by genotyping the nascent offspring for Sex-determining Region Y (SRY), indicating male sex (Larney, Bailey, & Koopman, 2014). This would allow for us to group offspring not only by litter and maternal dietary regimen, but also sex, making sex-specific differences in all early life indices detectable.

## Methods:

### Animal care and use:

Upon birth, litters were counted and individual pups were weighed to the nearest 0.1 gram within 24 hours. At postnatal day 3, litters were reduced to four (two males and two females, when feasible) to standardize milk supply. At 21 days, pups were weaned by sex and maternal treatment group. Upon weaning, animals are allowed 24-hour access to chow (5% fat, 24% protein, 3.7% sucrose, 32% starch, 2.91 kcal per gram) and water.

### Body composition:

Body weight was assessed using a scale to the nearest 0.1 gram (). This was assessed at birth, 7, 14, and 21 days of life. At PND 21, weekly indirect body composition assessment using EchoMRI was conducted, generating fat mass, lean mass, and free water measurements in addition to body weights.

### Survival:

Survival of pups will be assessed by counting the number of pups in each litter each day until PND 3.

### Determination of sex:

In order to determine sex, at PND3, anogenital distance of each pup will be evaluated. Those pups with greater anogenital distances will be designated male, and those with lesser distances, female. This will be confirmed by genotyping the fetal tissue for expression of SRY, which is carried on the Y chromosome and is causal in phenotypic sexual determination (Larney et al., 2014).

### Reduction of litters:

Because maternal milk supply may differ based on number of pups, milk supply will be standardized after the initiation of the lactational period. At PND 3, litters will be reduced to 4 when possible (2 male, 2 female). This will help to ensure each dam can supply sufficient and equal amounts of milk to each pup.

### Food intake:

Food intake monitoring began at weaning. Weekly food intake was measured in grams for each cage, and food intake in calories was computed by taking the total food intake per week and dividing by number of animals in each cage. At 65 days of age, animals were switched to *ad libitum* feeding with high fat diet (HFD) (45% fat, 20% protein, 17% sucrose, and 7% starch, 4.73 kcal per gram). Animals will remain on HFD for 10 weeks.

### Insulin Sensitivity:

*Insulin tolerance test:*

After 6-hour fast, blood glucose was taken using a glucometer and tail clip. Animals were given intraperitoneal insulin injections (0.75 units/kg body weight; Humulin U100 in cold, sterile-filtered phosphate buffered saline (PBS)) and blood glucose was tested using a glucometer at 15-minute intervals for 2 hours. If animals began to exhibit moribund behaviors, 300 units of 10% glucose in PBS was administered, the animal was then removed from the experiment, and subsequent blood glucose measurements were omitted from data analysis.

*Glucose tolerance test:*

*Sacrifice data:*

* Fasted 16 hours
* Btw 9-12
* Blood/serum
* Liver, iWat, gWAT, Quad – no weights
* Liver histology
* Body weight
* FBG

### Statistical Analyses:

All statistical analyses were completed in R (version \_\_\_\_\_). Repeated measures, such as body weight, body composition, food intake, and insulin tolerance testing utilized mixed linear modeling (LME4 package) with each animal assessed as a random effect. All models were tested for sex-interaction. Models were built bottom up and were tested in pairs using ANOVA. Models where ANOVA p value was <0.05 were considered statistically significant.

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**Determine the effect of** **early time-restricted feeding in the perinatal period on offspring health.**