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# Specific Aim 2

**Identify the relationship between glucocorticoid exposure during lactation and mammary gland function.**  Postpartum corticosteroid prescription proportion was recorded at 2.4 per 1000 women in a Danish cohort from 1991-1996 (Olesen *et al.*, 1999). It is reported that postpartum corticosteroid use is low since late pregnancy use is linked with delayed lactation initiation depending on the course and timing of treatment (Anon, 2006). The specific mechanisms by which glucocorticoid exposure at preconception, during pregnancy, or during lactation affects mammary gland function remain unclear. Current studies have not thoroughly assessed the effects of glucocorticoid exposure on the development and function of mammary glands. Many of the studies are conducted with ovine models and much less data is available on rodent models or humans. For humans, there are no contraindications to taking glucocorticoids during lactation or pregnancy. Data regarding potential side effects is lacking, and medical consensus is that the treatment benefits of critical conditions like asthma or irritable bowel syndrome outweigh potential harms. My hypothesis is that maternal glucocorticoid exposure will impair mammary gland development, reduce milk output and macronutrient composition ultimately leading to reduced offspring growth prior to weaning and impaired adult metabolic health. To test this, we will test how a) dexamethasone exposure affects mammary gland size and development, b) how dexamethasone exposure affects milk output volume and carbohydrate, protein and fat composition, and c) the effect of the exposure on offspring health via assessing body composition and glucose tolerance.

# Rationale and Background

Glucocorticoids are important for proper mammary gland development (Anderson & Turner, 1956). Primarily, prolactin is the main hormone that promotes the transcriptional activity of STAT5 and mediates mammogenesis- the development of the alveolar duct in preparation for lactation (Feng *et al.*, 1995; Yang & Friedl, 2015). Currently, there are no contraindications to using glucocorticoids during lactation for asthma, allergies, irritable bowel syndrome and other symptoms. Nevertheless, lactating women are advised to breastfeed 4 hours after treatment to minimize transfer of glucocorticoids to the newborn via milk[[1]](#footnote-1). Evidence regarding the effects of glucocorticoids on mammary gland development in preparation for lactogenesis II and during lactation remains very scarce (Anon, 2006).

It appears that the effects of glucocorticoids may be more essential for normal growth at low doses during early pregnancy when the alveolar ducts are still developing with a negative effect at high doses. At midgestation, alveolar development seems to be almost complete as their capacity to produce milk seemed intact despite glucocorticoid treatment (Henderson *et al.*, 2009). Glucocorticoid exposure near preterm delivery had time-dependent effects on lactogenesis II initiation (Henderson *et al.*, 2007). Glucocorticoid exposure at weaning prolongs lactogenesis and inhibit mammary gland apoptosis (Feng *et al.*, 1995). The mechanisms by which glucocorticoids mediate their effect on mammary gland development remain poorly understood. Furthermore, milk output and macronutrient composition after glucocorticoid exposure during pregnancy and/or lactation is insufficient in rodents and humans.

## Glucocorticoids are Required for Mammary Gland Development

Prolactin is also responsible for milk synthesis, while oxytocin promotes milk ejection by alveolar contractions (Anon, 2009). Dexamethasone was found to work in collaboration with prolactin to coactivate the prolactin/STAT5 and GC/GR pathways that drive milk production in a synergistic manner (Kobayashi *et al.*, 2016). Dexamethasone alone was not found to promote milk synthesis but instead augmented prolactin-induced casein secretion (Kobayashi *et al.*, 2016). In adrenalectomized rats, mammary gland size was reduced, suggesting the importance of glucocorticoids (Anderson & Turner, 1956). Upon injection of prednisone to adrenalectomized-ovariectomized rats, mammary gland development was normalized to the size in ovariectomized rats (Anderson & Turner, 1956). In hypophysectomized-ovariectomized-adrenalectomized mice, cortisol acetate treatment improved mammary gland ductal branching (NANDI, 1958).

## Glucocorticoid Excess Reduces Mammary Gland Development and Function

Treatment with deoxycorticosterone acetate at lower doses improved ductal branching but caused mammary gland regression at higher doses (NANDI, 1958). Despite the need of both prolactin and glucocorticoids for normal development of mammary glands, the effects of glucocorticoids on lactation remain conflicting and scarce. Dexamethasone administration in lactating rats after a short and prolonged period of pup separation showed inhibition of suckling-induced prolactin release that later normalized (BARTHA *et al.*, 1991). This indicates a potential direct inhibitory effect of cortisol on pituitary prolactin production. In concordance with this, adrenalectomized and dexamethasone-treated male rodents had reductions in prolactin levels (BARTHA *et al.*, 1991). As a drop in glucocorticoid level is necessary to promote involution, exogenous glucocorticoid exposure after suckling cessation has been shown to prevent mammary gland involution and was shown to preserve alveolar structure and increase alveolar size in mice (Feng *et al.*, 1995; Li *et al.*, 1997). Lactating PND6 rats that received dexamethasone just prior to nursing had impaired suckling (Vilela & Giusti-Paiva, 2011). In the dexamethasone group, oxytocin and prolactin levels were lower than the control groups that received saline. Furthermore, pups of dexamethasone-treated rats gained less weight after nursing, suggesting that milk volume was impaired (Vilela & Giusti-Paiva, 2011). In a case study, a lactating woman who received local corticosteroid injection reported cessation of milk production 30 hours post injection with a spontaneous resumption of lactation within another day (Babwah *et al.*, 2013). Furthermore, in preterm deliveries, maternal betamethasone treatment had a time-dependent effect on milk volume but not composition (Henderson *et al.*, 2007). Women who delivered within two days of the treatment had increased milk volume compared to women who delivered 3-9 days post-treatment. This indicates an immediate postpartum effect of glucocorticoids on mammary gland function.

## Glucocorticoid-Dependent Effects on Milk Composition

Glucocorticoids can also have an impact on milk composition. In most tissues, glucocorticoids reduce protein synthesis by inhibiting mTORC1 and activating FOXO1/3 (Wang *et al.*, 2006; Wolff *et al.*, 2014)*.* Dexamethasone exposure in cows reduced milk output volume to its lowest after one day of treatment, then gradually increased afterward (Shamay *et al.*, 2000). Lactose levels in milk were unaltered, while milk protein and fat percentages increased reaching a maximum after one day of treatment then gradually decreased to normal within 3 days with a prolonged reduced concentration of whey protein (Shamay *et al.*, 2000). Owing to the reductions in total volume, the total protein and fat yield were reduced. Similarly, adrenocorticotropin injection in lactating cows reduced milk yield and protein yield after injection (Varner & Johnson, 1983). Lactose is thought to be the main regulator of milk output (Kronfeld & Hartmann, 1973). Hence, the reduced milk macronutrient yield was suggested to be due to mammary gland’s reduced ability to utilize glucose for lactose synthesis after glucocorticoid treatment (Varner & Johnson, 1983).

During lactation, maternal glucocorticoids can cross to the offspring through milk by passive diffusion due to their lipid-like profile (Hollanders *et al.*, 2017). Cortisone is reportedly higher in milk than cortisol, and this is thought to be due to HSD11B2 activity in the mammary epithelial cells (Smith *et al.*, 1996; Hollanders *et al.*, 2017). Following the maternal diurnal rhythm, maternal plasma glucocorticoid levels are highest in the early morning at 7am, and milk cortisol concentrations were found to be associated with maternal plasma levels (Patacchioli *et al.*, 1992; van der Voorn *et al.*, 2016).

## Effects of Lactational Glucocorticoid Exposure on Offspring Health

The long-term effects of lactational glucocorticoid exposure on the offspring remain largely unknown. Children of mothers who used glucocorticoids during pregnancy had an altered stress response and altered neurodevelopment (Alexander *et al.*, 2012; Asztalos *et al.*, 2014). The effects of corticosteroid use further manifest in childhood where maternal third trimester cortisol levels were shown to influence childhood adiposity (Entringer *et al.*, 2016). In mice, studies have shown reduced placental weights after a short period preterm exposure to dexamethasone and potential fetal growth restriction (Cuffe *et al.*, 2011).

In one study on lactating rats, the investigators used prolonged maternal dexamethasone exposure at a dose of 100ug/kg/day on PND1-7, 1-14, and 1-21 (Jeje & Raji, 2015). At PND14 and 21 and at 12 weeks of age, offspring of dams exposed to maternal glucocorticoids at PND1-7, 1-14, and 1-21 had significantly reduced body weights. Offspring lipid profile at 12 weeks of age showed increased liver cholesterol, low-density lipoproteins, and triglycerides with reduced liver high-density lipoprotein levels along with elevated fasting blood glucose (Jeje & Raji, 2015). The effect of this exposure on offspring kidneys at 12 weeks of age, showed signs of necrosis and increased oxidative stress (Jeje *et al.*, 2016). In this chapter, we will investigate the effects of lactational dexamethasone exposure in mice with the following three aims.

**Aim 2.1:** Is mammary gland development altered after maternal glucocorticoid exposure during lactation?

**Aim 2.2:** How does maternal glucocorticoid exposure during lactation affect milk output and macronutrient composition?

**Aim 2.3:** Is offspring metabolic health altered after maternal glucocorticoid exposure during lactation?

# Experimental Design

To assess the effects of glucocorticoids on milk production and milk volume, we will obtain NUMBER (n=X for each of the four groups) 8-week old virgin C57BL6/J female and male mice from The Jackson Laboratory. Mice will be given two weeks to acclimatize with *ad libitum* access to normal chow diet and water. After acclimatization, dams will be assigned to one group of the following: control PND0.5-16.5, experimental PND0.5-16.5, control PND0.5-21.5, or experimental PND0.5-21.5 (See Figure 1). After being assigned a group, the dams will be mated with age-matched males and *ad libitum* normal chow diet and water. Male breeders from both cohorts will be removed from the cage after 18 days of mating to avoid the occurrence of a second pregnancy.In all groups, the dams will undergo body mass assessment three times weekly throughout the experiment and immediately postpartum using magnetic resonance to assess body composition. We will measure dam food and water intake weekly. We will check for litters on a daily basis after 2.5 weeks of mating. After delivery (PND0.5), the dams will either receive water (controls) or dexamethasone (experimental) at a dose of 1mg/kg/day. Pups will be sexed then culled to four animals (2 females and 2 males, if possible) per litter at PND2.5. The offspring will be weighed at PND0.5, PND7.5, 14.5, 16.5 (for PND0.5-16.5 groups only), and at 21.5 (for PND0.5-21.5 groups only). Control and experimental groups of PND0.5-16.5 will receive water or dexamethasone throughout lactation and until PND16.5, where the dams and the pups will be sacrificed and maternal mammary glands will be weighed and collected for cryosectioning and molecular studies. Control and experimental groups of PND0.5-21.5 will be allowed to complete nursing fully and the pups will be weaned to evaluate effects on the offspring.

The pups of groups PND0.5-21.5 will be weaned into new cages based on sex and treatment group. The weaned pups will have *ad libitum* access to normal chow diet and water. Their water and food intake will be assessed weekly. They will further undergo body composition analysis by echoMRI at weaning and weekly thereafter. To assess glucose homeostasis, a glucose tolerance test (GTT) will be done at 6 weeks of age followed by sacrifice and tissue collection of fat pads 3 days later. Their fat pads (gWAT and iWAT) will be collected for molecular studies to assess mTORC1 protein expression via Western blotting.

### Figure 1: Diagram representing the experimental design and respective timeline



# Methods

## Dexamethasone Exposure

Water-soluble dexamethasone (Sigma) will be prepared at a concentration of 53 mg/L, which our previous work shown results in a dose of approximately 1 mg/kg/day in non-nursing mice.

If the dam is single housed or with nursing pups:

(the new added total water/dexamethasone- the last measurement’s water/dexamethasone) / # of days between measurements

If more than one adult mouse is in the cage (when the male is breeding in the same cage), food intake will be calculated as follows:

(the new added total water/dexamethasone - the last measurement’s water/dexamethasone) \* #of days between measurements / sum of days spent by each mouse in that cage between measurements

## Food Intake

Food will be weighed when the breeding cages are set up for mating. The weight of the dam’s food will be recorded three times weekly every Monday, Wednesday, and Friday. Food will also be weighed at delivery for the dam. Food will be topped off to ~400g weekly every Friday. Food intake will be calculated as:

If the dam is single housed or with nursing pups:

(the new added total food weight - the last measurement’s food weight) / # of days between measurements

If more than one adult mouse is in the cage (when the male is breeding in the same cage, or when weaned offspring are housed together), food intake will be calculated as follows:

(the new added total food weight - the last measurement’s food weight) \* #of days between measurements / sum of days spent by each mouse in that cage between measurements

## Body Composition

Mice will be weighed by using dynamic weighing to capture accurate weight using a digital scale. The weight will be recorded along with the mouse ear tag number. The mouse will be gently placed in the MRI tube with the plunger slightly compressing along the mouse body to ensure it cannot move during the measurement. Fat, lean, free water and total water mass (g) will be recorded for each animal.

## Sacrifice and Tissue Collection

All animals will be sacrificed using anesthetic gas inhalation (5% isoflurane drop jar). Cervical dislocation will be done as a secondary method to confirm euthanasia. The mice will be pinned on a dissection board in a supine position. For dams from control and experimental groups PND0.5-16.5, we will dissect the mammary glands by a midline incision of the skin from the rectum to the diaphragm, extract thoracic, abdominal and inguinal mammary glands. The peritoneum will be pulled apart from the skin. The lower glands will be excised carefully then weighed. A portion of the upper and lower glands will be embedded in paraffin for histology, while the rest will be collected in 2ml tubes and snap frozen in liquid nitrogen then alter stored at -80C for possible future molecular studies. Offspring of dams from control and experimental groups PND0.5-21.5 will be sacrificed similarly at 6 weeks of age. For the offspring, fat pad collection will be done. Inguinal white adipose tissue (iWAT) will be collected from the mouse right side first by pulling the peritoneum away from the skin. Inguinal fat will be carefully extracted, weighed then snap frozen in liquid nitrogen for further molecular studies. Right gonadal white fat tissue (gWAT) will be collected next by scraping the fat along the gonads (ovaries or testis), weighed, and then snap frozen in liquid nitrogen in 2ml tubes. The fat pads will be stored at a temperature of -80C.

## Determining Milk Output Volume

At PND10.5, we will determine milk output volume for the control and experimental groups PND0.5-16.5. To determine milk volume, we will use the weigh-suckle-weigh technique (Boston *et al.*, 2001). Briefly, we will weigh the dam then determine the aggregate weight of the pups. The dam and pups will then be separated for two hours. During the two-hour separation, the pups will be placed in a new cage and will be kept warm using a heating pad. In the meantime, the dam will remain in its initial cage with *ad libitum* access to normal chow diet and water or dexamethasone-water based on its assigned group. After the two-hour separation period, the dam will be weighed again and the aggregate weight of the pups will be measured. The pups will then be returned to the dam’s cage and will be allowed to nurse for one hour. At the end of the nursing timepoint, the dam will be weighed and the aggregate weight of the pups will be determined. After the one-hour nursing period, milk volume will be determined as the weight change of the pups after nursing and after the 2-hour separation. The difference in the dam’s weight after nursing and after the 2-hour separation will help further ascertain the dam’s milk supply.

## Determining Milk Composition

On PND16.5, we will collect milk samples (~0.5ml) from the nursing dams in groups control and experimental PND0.5-16.5. Briefly, we will separate the dam and pups for 2 hours. The pups will be weighed and will undergo body composition assessment using echoMRI. Afterwards, the pups will be sacrificed using isoflurane and a secondary measure of cervical dislocation. We will anesthetize the dam after two hours of separation by intraperitoneal injection of Ketamine (0.1275g/kg body weight). We will then perform an intraperitoneal injection of oxytocin into the forelimb (2U/dam) to induce milk production. The dam’s nipples will be manually squeezed to promote milk letdown, and the milk will be collected into a 1.5 ml tube via suction. After milking is complete, the dam will immediately be sacrificed using isoflurane and a secondary measure of cervical dislocation. We will then dissect the dam by a midline incision of the skin, extract thoracic, abdominal and inguinal mammary glands. The lower mammary gland pads will be weighed. A small section of the lower mammary glands will be saved for paraffin embedding for histology while the rest will be snap frozen in liquid nitrogen and cryopreserved to later determine mTORC1 expression as previously discussed via Western blotting. Milk protein composition will be analyzed using SDS-PAGE gels and diluted milk samples.

## Determining Milk Protein Concentrations

Milk samples collected from control and experimental groups of PND0.5-16.5 will be assessed for protein content. Milk will be diluted to a factor of 4 (1:3 in PBS+EDTA). Skimmed milk will be collected after centrifuging. Samples will be heated to ~95C and loading cocktail will be added onto the plastic plate with the gel along with a ladder. Gels will be stained by Coomassie blue and quantified by near-infra-red imaging. Imaging will be done using LiCor Odyssey to determine levels protein of whey acidic protein, alpha casein, beta casein, lactose, and serum albumin identified based on known molecular weights.

## Determining Milk Fat Content

Milk samples collected will be assessed for fat content by the creamatocrit method using a hematocrit centrifuge. Briefly, samples will be diluted to a factor of 3 (1:2 in PBS) into well-sealed capillary tubes. The tubes will be placed in CritSpin mini-creamatocrit spinner. Samples will be centrifuged for 8 cycles of 120 seconds. The capillary will form layers of white fat and non-fat milk. The distance of the fat layer will be measured in millimeters (mm) accurately. The total volume of milk (fat + non-fat milk) will be measured in mm. Percentage of fat will be determined with respect to the total volume.

## Glucose Tolerance Test

Weaned offspring in groups control and experimental PND0.5-21.5 will undergo a glucose tolerance test (GTT) being challenged with 1g/kg of lean body mass (determined by echoMRI) after a 6-hour fast with *ad libitum* access to water. The effects of maternal glucocorticoid exposure during lactation on offspring adolescent glucose sensitivity will be determined. Briefly, after the fast, the tail will be cut to allow for blood sampling via AccuCheck Advantage Glucometer. Tail vein blood will be immediately measured at 0minutes after the 6-hour fast to denote fasting blood glucose. Mice will be injected by a syringe into the interperitoneal cavity with the appropriate glucose dosage. The timer will be set as to allow for blood collection every 15 minutes. Blood will be collected at 5, 30, 45, 60, 75, 90 and 120 minutes after injection. After the GTT is done, mice will have *ad libitum* access to normal chow diet and water again. These data will be analysed by mixed linear models of glucose at each time point

## Western Blotting

Using the fat tissues collected from offspring of groups PND0.5-21.5, gWAT and iWAT will be assessed for mTORC1 activity. Briefly, a portion of the sample will be boiled and loaded into different wells with a ladder control. Proteins will transfer to nitrocellulose overnight. The matrix will be stained for total protein using Revert total protein and scanned by LiCor to normalize against total protein. Samples will be incubated with the primary then the secondary antibodies. Briefly, antibodies against total and phosphorylated mTORC1 targets (S6K, 4EBP1, S6) and regulators (Akt, IRS and TSC2) will be used.

## Histology

Mammary glands collected from control and experimental groups PND0.5-16.5 will be embedded in paraffin and stained at the Rogel Cancer Center’s Tissue and Molecular Pathology. Slides will be blindly assessed adipocyte size and alvelolar number..

# Expected Results

## Aim 2.1: Is mammary gland development altered after maternal glucocorticoid exposure during lactation?

I hypothesize that our prolonged dexamethasone exposure will cause reductions in mammary gland development at PND16.5. This will be evident in the reduced size of the glands and the reduced adipocyte size. Rats treated with corticosteroids for 4 weeks had reduced mammary gland branching. The effects of corticosteroid treatment were dose-dependent, by which higher doses caused further reductions in mammary gland area and branching (Zhu *et al.*, 1998). Despite the need of low doses of glucocorticoids for normal development of mammary glands, administration of deoxycorticosterone acetate at high doses caused mammary gland regression in mice (NANDI, 1958). Since glucocorticoid treatments show reductions in mammary gland development, proving necessary to control carcinogenesis (Zhu *et al.*, 1998), and since high doses ultimately reduce mammary gland size (NANDI, 1958),

## Aim 2.2: How does maternal glucocorticoid exposure during lactation affect milk output and macronutrient composition?

As prior studies show that a short-term glucocorticoid exposure reduced macronutrient yield but increase percentage, I hypothesize that our prolonged exposure will increase milk protein and fat macronutrient percentage. As lactose is the regulator of milk output, reductions in milk and lactose yield will be simultaneous (Varner & Johnson, 1983). Hence, I hypothesize that dexamethasone exposure will have unaltered lactose percentage despite the reductions in the milk yield. The hypothesized results are in agreement with the previous hypothesis suggesting reduced mammary gland development in Aim 2.1, as a less developed mammary gland will yield less milk with altered macronutrient composition. The known effects of glucocorticoid exposure on milk volume and composition are based on a one-time or short-term exposure. Dexamethasone exposure 2 hours prior to suckling in lactating rats caused reductions in the suckling-induced prolactin response (BARTHA *et al.*, 1991). Dexamethasone exposure in lactating rats after prolonged dam-pup separation caused reduced oxytocin and prolactin levels after a 15-minute suckling stimulus (Vilela & Giusti-Paiva, 2011). This exposure also reduced pup weight gain after 15 minutes of suckling indicating reductions in milk output (Vilela & Giusti-Paiva, 2011). Furthermore, lactating cows exposed to dexamethasone had reduced milk output a day after injection, which later normalized within 5 days (Shamay *et al.*, 2000). A case study of a lactating woman who received one course of a glucocorticoid treatment showed reductions in milk production 30 hours after treatment which later normalized within the next day (Babwah *et al.*, 2013). As for milk composition, cow exposure to dexamethasone caused reduced lactose, protein, and fat yield but showed increased protein and fat percentages since milk output overall was reduced (Shamay *et al.*, 2000). Adrenocorticotropin exposure reduced protein yield along with reduced milk yield in cows (Varner & Johnson, 1983). As prolactin signaling is necessary for milk synthesis, impaired signaling caused by dexamethasone is expected to reduce milk synthesis. Additionally, given the witnessed reductions in milk output in human and animal models after brief exposure to glucocorticoids, I hypothesize that our exposure will reduce milk output.

Aim 2.3: Is offspring metabolic health altered after maternal glucocorticoid exposure during lactation?

Based on prior results, I predict that …. Offspring of dams treated with dexamethasone at PND1-7, 1-14, and 1-21 showed reduced weights at PND14 and 21 and at 12 weeks of age compared to controls (Jeje & Raji, 2015). Offspring had higher fasting blood glucose at 12 weeks of age along with an impaired lipid profile. Given the altered milk yield and composition and the findings by Jeje and Raji (2015), I hypothesize that offspring will have lower body weights at PND14.5, 16.5 (from groups of PND0.5-16.5 only), 21.5 (for groups PND0.5-21.5 only), and weekly afterwards until week 6 of age when the offspring will be sacrificed (for groups PND0.5-21.5 only). Furthermore, given then altered glucose and lipid profile of offspring (Jeje & Raji, 2015), I hypothesize fat mass in experimental offspring will be higher despite an overall reduced body weight. When offspring undergo the GTT at 6 weeks of age, I expect that experimental offspring to have higher fasting blood glucose with impaired glucose tolerance. Since glucocorticoids pass through the milk to the offspring (Hollanders *et al.*, 2017) and since they promote adipogenesis (Patel *et al.*, 2014), I hypothesize that fat pads collected from offspring of experimental group PND0.5-21.5 will have higher mass than controls. mTORC1 activity in offspring adipocyte is expected to be higher in experimental offspring, as mTORC1 activity regulates adipogenesis (Magdalon & Festuccia, 2017). The offspring phenotype given reduced body weight and increased fat mass will reflect a thin-fat phenotype. Future studies will explore the molecular underpinnings of these phenotypes.

Potential Pitfalls and Alternate Approaches (Aims 2.1-2.3)

It is possible that the chronic dexamethasone exposure will drastically reduce mammary gland capacity to produce milk, making it impossible to nurse pups and ultimately leading to pup death. In that case, we will alter dexamethasone exposures in new cohorts with treatment windows as follows: PND1-7, PND7-14, and PND14-21. This will allow us to determine more accurately when the effects of dexamethasone are most critical on the offspring.

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