Activation of adipocyte mTORC1 increases milk lipids in a mouse model of lactation.

**Author names and affiliations:**

Noura El Habbal1, Allison C. Meyer1, Hannah Hafner2, JeAnna R. Redd1, Zach Carlson2, Molly C. Mulcahy1, Brigid Gregg1,2, and Dave Bridges1

1Department of Nutritional Sciences, University of Michigan School of Public Health, Ann Arbor, Michigan, U.S.A.

2Department of Pediatrics, University of Michigan Medical School, Ann Arbor, Michigan, U.S.A.

**Corresponding author:**

Dave Bridges Email address: [davebrid@umich.edu](mailto:davebrid@umich.edu)

Postal address: 3866 SPH I 1415 Washington Heights, Ann Arbor, Michigan 48109-2029 Telephone: +1 (734) 764-1266

**Declaration of Interests**

The authors have no competing interests to declare.

# Abstract

Milk is the primary nutrient source for newborns. The contributions of mammary adipocytes and the intersections between nutrient sensing and milk lipids are not fully understood. A major nutrient sensor in most tissues is the mechanistic target of rapamycin 1 (mTORC1). In this work, we used a model of adipocyte mTORC1 hyperactivation to evaluate mammary gland structure, function, milk composition, and offspring weights with an Adiponectin-Cre driven *Tsc1* knockout. Our results show that knockout dams have higher milk fat composition, contributing to higher milk caloric density and heavier offspring weight during lactation. Additionally, milk of KO dams displayed a lower percentage of saturated fatty acids, higher percentage of monounsaturated fatty acids, and a lower milk ω6: ω3 ratio driven by increases in DHA. Gene expression analyses identified changes in eicosanoid metabolism, adaptive immune function and contractile gene expression. Together, these results suggest a novel role of adipocyte mTORC1 in mammary gland function and morphology, milk composition, and offspring health.

**Key words**: Mammary glands, Milk composition, Adipocytes, mTORC1, Polyunsaturated Fatty Acids

# Introduction

Maternal obesity increased by 11% from 2016 to 2019 and has reached 29% (1). The health of offspring is highly influenced by intrauterine and early postnatal exposures (2). During early postnatal life and the critical developmental window of lactation, maternal obesity can impair the ability to initiate and sustain breastfeeding and can alter milk composition (3). Initiation of lactation is delayed in pre-pregnancy obese or overweight women (4) while the duration of breastfeeding for 6 months or more is shorter (5). The probability of early weaning at 3 months postpartum was highest for infants of obese mothers (6). In addition to altering lactation initiation and duration, maternal obesity can impact milk composition. Maternal weight, body mass index, fat mass, and fat mass percentage were positively correlated with total and true milk protein content at 3 months postpartum (7). Maternal weight and body mass index were positively correlated with milk fat content at 1 month postpartum (7). Furthermore, the fatty acid composition showed a higher ω6:ω3 ratio in milk of obese women compared to their non-obese counterparts (8).

Successful lactation requires the development and differentiation of the mammary glands in preparation for milk production and secretion (9, 10). The mammary gland is composed of several cell types including adipocytes, contractile muscles and alveolar cells. Mammary adipocytes are necessary for proper gland development and structure (11, 12). The mammary adipocytes in close proximity to the alveolar epithelial cells are thought to provide a primary lipids for milk production (13). Given their role in maturation, development, and function of the mammary gland, mammary adipocytes are crucial for successful lactation.

Obese subjects have increased activity of the mechanistic target of rapamycin complex 1 (mTORC1) in the visceral fat compartment (14). mTORC1 is a critical nutrient sensor and a main regulator of protein and lipid synthesis (15, 16). In the presence of anabolic signals like insulin, energy abundance, and amino acid availability, mTORC1 function is upregulated via the Akt pathway (17). mTORC1 promotes lipogenesis and adipogenesis and inhibits lipolysis (15, 18). Hyperactivation of mTORC1 in the mammary epithelium impairs development of non-lactating mammary glands (19), but little is known about its role in adipocytes with respect to macronutrient synthesis during lactation (20). Using a conditional *Tsc1* knockout genetic model, we show that chronic mTORC1 activation in maternal adipocytes, increases adipocyte number and volume, increases milk fat composition and alters milk lipid composition, reduces gene expression of immune response pathways in the mammary glands, and increases weight of lactating offspring.

# **Materials and Methods**

## Animal Husbandry

All mice were purchased from the Jackson Laboratory. All mice were fed a normal chow diet (Lab Rodent Diet; 5L0D) with *ad libitum* access to food and water. To hyperactivate adipocyte mTORC1 and generate an adipose-specific *Tsc1* knockout, *Tsc1*fl/fl mice (JAX stock #005680) (21) were crossed with *Adipoq*-Cre (JAX Stock #010803) (22) mice expressing the adipocyte-specific constitutive Cre recombinase controlled by adiponectin gene promoter. The parental strains (F0) for this experiment were 6-8 week old male *Tsc1*fl/fl; CreTg/+ or *Tsc1*fl/fl; Cre+/+ crossed with 6-8 week old female *Tsc1*fl/fl; +/+ or *Tsc1*fl/fl; Tg/+, respectively. The offspring (F1) were a combination of knockout (KO, *Tsc1*fl/fl; CreTg/+) and wild-type (WT, *Tsc1*fl/fl; Cre+/+)mice. The knockout of the floxed alleles are driven by Adiponectin-Cre, which is expressed in all adipocyte lineages (brown, white and mammary adipocytes) (23, 24). There is currently no known Cre driver that is specific to mammary adipocytes. All animal procedures were carried out in accordance with the National Institute of Health guide for the care and use of laboratory animals and was approved by the University of Michigan Institutional Animal Care and Use Committee prior to the work being performed.

Male breeders were removed from the cage after 16 days of mating to avoid the occurrence of a second pregnancy.We checked for litters on a daily basis after 2.5 weeks of mating. The number of pups born was recorded to determine maternal fertility and pup viability. After delivery (delivery day denoted as postnatal day 0.5, PND0.5), the dams continued to have *ad libitum* access to food and water.

Pups were sexed and culled to four animals (2 females and 2 males, when possible) per litter at PND2.5. The offspring were weighed at PND0.5, PND7.5, 14.5, 16.5. The pups underwent body composition analysis at PND16.5 and then were immediately sacrificed.

## Body Composition

In all groups, the dams underwent body mass assessment three times a week during pregnancy and lactation and on the day of delivery using magnetic resonance (EchoMRI 1100, EchoMRI, Houston, TX) to assess body composition. Mice were weighed by dynamic weighing to capture accurate weight using a digital scale. The weight was recorded along with the mouse ear tag number. The mouse was then gently placed in the MRI tube with the plunger slightly compressing along the mouse’s body to ensure restrained movement during the measurement. Fat, lean, free water and total water mass (g) were recorded for each animal.

## Sacrifice and Tissue Collection

All animals were sacrificed using anesthetic gas inhalation (5% isoflurane drop jar) at PND16. Cervical dislocation was conducted as a secondary method to confirm euthanasia. The mice were pinned on a dissection board in a supine position. We dissected KO and WT dams by a midline incision of the skin from the rectum to the diaphragm and extracted thoracic, abdominal and inguinal mammary glands. Briefly, the peritoneum was pulled apart from the skin. The lower glands were excised completely then weighed. Portions of the upper and lower glands were embedded in paraffin for histology, while the remaining tissue from the lower left and right mammary glands were collected in 2mL tubes and snap frozen in liquid nitrogen and later stored at -80°C for molecular studies. Offspring of dams were sacrificed without tissue extraction at PND16 after body assessment measurements.

## Determining Milk Output Volume

At peak lactation (PND10.5; (25)), we determined milk output volume for the WT and KO dams. To determine milk volume, we used the weigh-suckle-weigh technique (26). Briefly, we weighed the dam separately then determined the aggregate weight of the pups. The dam and pups were then separated for two hours. During the two-hour separation, the pups were placed in a new cage and were kept warm using a heating pad under the cage. In the meantime, the dam remained in its initial cage with *ad libitum* access to normal chow diet and water. After the two-hour separation period, the dam was weighed again and the aggregate weight of the pups was measured. The pups were then returned to the dam’s cage and were allowed to nurse for one hour undisturbed. At the end of the nursing timepoint, the dam was weighed again and the aggregate weight of the pups was measured. Milk volume was approximated as the weight change of the pups after nursing.

## Milk Composition Assessment

On PND16.5, we collected milk samples (~0.5mL) from the nursing dams. Briefly, we anesthetized the dam after two hours of separation from the pups by intraperitoneal injection of Ketamine (0.1275g/kg body weight). We then performed an intraperitoneal injection of oxytocin into the forelimb (2U/dam) to induce milk production. The dam’s nipples were manually squeezed to promote milk letdown, and the milk was collected into a 1.5 mL tube via gentle suction. After milking was complete, the dam was immediately sacrificed using isoflurane and a secondary measure of cervical dislocation. We then dissected the dam by a midline incision of the skin, extracted thoracic, abdominal and inguinal mammary glands. The left and right lower mammary gland pads were weighed. A small section of the right lower mammary glands was saved for paraffin embedding for histology while the remainder was snap frozen in liquid nitrogen and stored at -80°C for molecular studies.

Milk samples collected from WT and KO dams were assessed for fat content by the creamatocrit method using a hematocrit centrifuge (27). Four fold diluted samples were transferred into plain micro-hematocrit glass capillary tubes. The tubes were sealed from one end using Critoseal. The tubes were later placed in CritSpin mini-creamatocrit spinner. Samples were centrifuged for 8 cycles of 120 seconds per cycle for a total spin time of 16 minutes. The capillary formed layers of white fat and non-fat milk. The distance of the fat layer was measured using a 150 mm dial caliper (General Tools and Instruments 6” Dial Caliper). The total volume of milk (fat + non-fat milk) was also measured in mm. Percentage of fat was determined with respect to the total milk volume.

Lipidomic analyses were done by the Michigan Regional Comprehensive Metabolomics Core. Milk samples were frozen at -80°C until analysis to prevent lipid hydrolysis and peroxidation. Samples were quickly thawed once for lipidomic analysis without undergoing multiple freeze-thaw cycles. Long chain fatty acid concentrations were determined following sample extraction, semi-purification and derivatization followed by fatty acid measurement by gas chromatography (GC) using an Agilent GC equipped with flame ionization detector. Results were reported on 33 lipid classes from C14:0 to C24:1.

## Transcriptomic Analyses

Using the lower right mammary gland tissues collected from the dams, we assessed whole-transcriptome RNA expression using five wild-type and six knockout samples. RNA samples were prepared from the mouse tissues using the PureLink RNA Mini Kit. Briefly, tissues were cut on dry ice to ~50mg samples then homogenized and treated to collect the purified RNA. The RNA was quantified using a nanodrop and purity was verified by an Agilent Bioanalyzer. All samples had an RNA integrity number (RIN) higher than 7. Library preparation and next generation sequencing was conducted by the Advanced Genomics Core at the University of Michigan. Paired-end poly-A mRNA libraries were generated and sequenced to an average depth of 57M (range 46M-69M) reads/sample on Illumina NovaSeq (S4). Reads were aligned to the mouse reference genome GRCm38.p6 using Salmon v 1.3.0 (28) with the gc-bias and validateMappings flags. Mapping efficiency was 54.8% (sample range 53-56.6%). Transcript-level data was reduced to gene-level data via tximeta v1.8.4 (29) and txiimport v1.18.0 (30) prior to analysis by DESeq2 v1.30.1 (31). To determine differential expressed genes we evaluated 14242 genes, excluding those with low or no read counts, identifying 265 differentially expressed genes (q<0.05). Full gene expression results are reported in Supplementary Table 1. For gene set enrichment analyses, we used ClusterProfiler v3.16 after ranking genes by fold change and analyzing relative to Gene Ontologies. Similarities between enriched gene sets were calculated by Jaccard distances. Gene set enrichment results are presented in Supplementary Table 2. Data are available from GEO at accession number XXXX

## Mammary Gland Histology and Adipocyte Assessment

Mammary glands collected from WT and KO dams were embedded in paraffin and Hematoxylin and Eosin (H&E) stained at the Rogel Cancer Center’s Tissue and Molecular Pathology. Slides were blindly assessed for adipocyte size and count with one slide per mouse. Using an EVOS inverted fluorescent microscope, eight representative sections per slide were taken at a 10x objective and covered the entire tissue area. Mammary gland adipocytes were quantified using the software ImageJ using the Adipocyte Tools Macros Plugin (32). In analyzing our images the parameter filters for adipocytes using the processing options were set at minimum of 40 pixels, maximum of 1000 pixels, and 30 dilates, and the parameters for segmentation options were set at minimum of 600 pixels and maximum of 1500 pixels. Potential adipocytes that were blurry, cut off, or below the 20 pixels threshold were excluded from the assessment as it was not feasible to select and measure them accurately. Once these two parameters were set on the image, manual addition and deletion were performed to ensure adipocytes were properly identified. Once all the adipocytes were accounted for, they were analyzed using the ImageJ software. The calculated adipocyte numbers were normalized to the total mammary gland area that was imaged.

## Statistical Analyses

Statistical significance was designated at p<0.05 for this study. All statistical analyses were performed using R, version 4.0.2 (33). Data are presented graphically as mean +/- standard error of the mean. For longitudinal measurements including body composition, food intake, and pup weight gain, data were analyzed using mixed linear models using lme4 version 1.1-25(34). We tested for sex-modification of all outcomes involving both sexes and report these when significant. For pairwise testing, normality was assessed using Shapiro-Wilk tests, followed by homoscedasticity using Levene’s test. Pending these results, appropriate parametric or non-parametric tests were done. All raw data, statistical analyses and reproducible R code can be found at <http://bridgeslab.github.io/TissueSpecificTscKnockouts/>.

# Results

# To understand how activation of mTORC1 in adipocytes affects lactation we evaluated pregnant mice that were either wild-type (*Tsc1fl/fl; Adipoq-CreTg/+*) orknockout(*Tsc1fl/fl; Adipoq-CreTg/+*). Adipocyte *Tsc1* knockout (n=6) and wildtype (n=5) virgin dams were mated with a male having the opposite genotype. Experimental timeline and mouse models are shown in Figure 1A-B.

## Maternal Body Composition is Similar during Pregnancy and Lactation in Adipocyte *Tsc1* Knockout Mice

Dam body composition was measured every Monday, Wednesday, and Friday during pregnancy and lactation and on the days of delivery and sacrifice. Body weights were comparable between dams throughout the study (Figure 1C). Lean mass was also comparable between Adipocyte *Tsc1* knockout dams and WT dams (Figure 1D). KO dams had a slightly lower fat mass during pregnancy and during lactation (Figure 1E). While WT dams lost fat mass during lactation, KO dams gained 71% more fat mass compared to WT dams (Figure 1F, p<0.001). This was not explained by differences in food intake as KO and WT dams had similar food intake through pregnancy and lactation (Figure 1G).

## Adipocyte *Tsc1* Knockout Mice Have Smaller Mammary Glands, but More Adipocytes in those Glands

At sacrifice we examined the mammary glands from the adipocyte *Tsc1* knockout dams. At PND16.5, the lower abdominal and inguinal mammary glands were collected and weighed from KO and WT dams. As shown in Figure 2A, Adipocyte *Tsc1* knockout dams had a 21% reduction in mass of right lower mammary glands (p=0.042) and a 29% reduction in weight of the left lower mammary glands (p=0.001) compared to the WT counterparts.

Mammary glands were fixed and stained for histological analyses to assess the number and area of WT and KO mammary gland adipocytes (Figure 2B-H). Adipocyte *Tsc1* knockout mammary glands had 63% more adipocytes compared to the WT mice (Figure 2B, p=0.057), We then assessed the adipocyte area as a fraction of the total mammary gland and found that in the adipocyte *Tsc1* knockout, adipocytes occupied nearly twice the mammary gland area than the WT mammary adipocytes (Figure 2C, p=0.051).

The mean adipocyte area for KO and WT adipocytes was not significantly different (Figure 2D, p=0.36), however the distribution of sizes was different. KO mammary adipocytes had a significantly different variation in the distribution of adipocyte areas (Figure 2E, p<0.001). KO adipocytes had 52% more larger sized adipocytes (200-300 µm2) compared to WT (Figure 2F, p=0.039). In a similar vein, *Tsc1* knockout adipocytes had 46% fewer adipocytes in the smallest range of 0-100 µm2 compared to WT adipocytes (Figure 2F, p=0.060). Our results show histological differences with the adipocyte *Tsc1* knockout having more adipocytes, more larger adipocytes, and a higher percentage of total mammary gland area comprised of adipocytes, in spite of smaller mammary glands overall.

## Pups Born to Adipocyte *Tsc1* Dams are Heavier During Peak Lactation

Compared to wild-type animals, the average litter size across genotypes was similar (Figure 3A). Pups were culled to four pups per dam to normalize milk supply. There was no significant difference in pup weight at birth (PND0.5; Supplementary Figure 1A). At PND7.5, after adjusting for sex, pups born to adipocyte *Tsc1* knockout dams were 7% heavier than pups born to WT dams (Figure 3B, p=0.010). Females born to KO dams were 9% heavier than females born to WT dams (Figure 3B, p=0.044). Weights of males born to KO were 5% heavier although this was not significantly different (Figure 3B, p=0.142). At PND14.5 and PND16.5, there were no weight differences between groups or sexes (Supplementary Figure 1B). We hypothesize that this is because at later time points the pups are eating more chow-based food and relying less on maternal lactation.

## Adipocyte *Tsc1* Dams Produce Similar Volumes of Milk, but with a Higher Milk Fat Percentage and Increased Desaturation of Milk Fatty Acids

Based on the changes in offspring weight and mammary gland size and histology, we calculated the mass of milk produced per dam at PND10.5. This was calculated by a two-hour separation period and then as the difference between pup weight after nursing for one hour and pup weight before nursing. This was not significantly different between groups (Supplementary Figure 2A). Similar data were obtained by measuring the weight of the dams pre- and post- lactation (Supplementary Figure 2B). To evaluate milk fat, milk was extracted from dams at PND 16.5. Total fat analysis revealed that milk of adipocyte *Tsc1* knockout dams had 34% higher fat percentage than milk of WT dams (Figure 4A, p=0.024).

Based on this finding, we assessed the specific fatty acid components of the milk fat using GC-MS. These analyses a more desaturated and DHA-rich milk in the KO compared to the WT (full results in Supplementary Table 1 and Supplementary Figure 3). At an aggregate level, adipocyte *Tsc1* knockout dams produced milk with 11% lower saturated fatty acids (Figure 4B, p=0.008), 12% higher percentage of monounsaturated fatty (Figure 4C, p=0.009), but similar percentages of polyunsaturated fatty acids (Figure 4E). The MUFA/SFA ratio shows a 24% higher rate of desaturation from SFA to MUFA (Figure 4D, p=0.004).

While PUFA’s overall were similar between groups, adipocyte *Tsc1* knockout milk had 28% higher levels of ω-3 fatty acids (Figure 4F, p=0.013), driven primarily by a 42% increase in the ω-3 fatty acid Docosahexaenoic acid (DHA) (Supplemental Figure 4, p=0.031). There was a similar percentage of ω-6 fatty acids (Figure 4G), resulting in a 31% lower ω-6: ω-3 ratio (Figure 4H, p=0.008). No individual ω-6 fatty acids differed between groups. Interestingly, the upstream precursors of DHA including ALA and EPA were largely similar, suggesting that ALA/EPA/DPA conversion into DHA may be increased (or selective sparing of DHA occurs) in the adipocyte *Tsc1* knockout dams.

## Suppressed Expression of Adaptive Immune Markers and Increased Expression of Muscle Biosynthesis Genes

To understand the mechanisms by which adipocyte mTORC1 activation affects mammary gland gene expression we performed bulk RNAseq on mammary gland explants from lactating wild-type and knockout dams. We identified 139 significantly differentially expressed genes between these groups (Figure 5A-B, and Supplementary Table 2). In spite of the observed differences in milk fat, and milk fatty acid composition, we were surprised that most fatty acid and triglyceride synthesis enzymes were similar between groups (Figure 5C). Several markers of adipogenesis and PPAR were upregulated including *Plin4, Adipoq, Cav2,* and *Fabp4*, consistent with the observed increase in adipocyte numbers (see Figures 5D and 2B). There were no detectable changes in PPAR transcripts. We also identified several genes involved in ω-3 eicosanoid metabolism and including the enzymes *Cyp2e1*, *Gpx3*, *Ephx2*, and *Pla2g4a*, whereas the ω-6 generating enzyme COX1 (*Ptgs1*) was significantly downregulated (Figure 6E).

In spite of the modest numbers of significantly differentially expressed genes, gene set enrichment analyses identified a 220 significantly differentially expressed biological pathways (180 downregulated, 40 upregulated; Supplementary Table 3). By identifying overlap of the genes in these pathways, they fell largely into two clusters of significantly differentially expressed pathways, one set related to the downregulation of adaptive immune differentiation and function, and another related to upregulation of striated muscle function (Figure 6F). To further explore the potential effects on adaptive immune cell function, we examined the expression of the T-cell marker genes encoding for CD3 and the B-cell marker genes encoding for CD45 and CD19. Each of these markers were reduced 20-92% suggesting a potential reduction in adaptive immune cells in these mammary glands.

# Discussion

Milk fat is the most variable macronutrient in human milk, and contributes the most to differences in energy content of milk (35). In this study we show that hyperactivation of adipocyte mTORC1 via adipocyte specific deletion of *Tsc1* alters milk fat composition and mammary gland adipocyte histology. Importantly, our approach is expected to activate mTORC1 in all adiponectin-expressing cells, including both peripheral and mammary adipocyte depots (23, 24). The positive role of mTORC1 in adipocyte biology has been well established. mTORC1 is necessary for adipocyte differentiation in both peripheral (36–38) but less is known about its role in mammary adipocyte differentiation and growth during lactation. ~~and mammary adipocyte depots (39, 40).~~ It is interesting that we observed increased adipocyte numbers, and elevated markers of differentiation in adipocyte *Tsc1* knockout mammary glands, as the Adiponectin-Cre is not expected to be activated until late in differentiation. It is also worth noting that there is evidence of de- and re-differentiation of post-involution mammary adipocyte, but to avoid this concern our studies focused on mice in their first pregnancy. The increased adipocyte hyperplasia could suggest a signal promoting mammary adipogenesis derived from peripheral adipocytes.

Once adipocytes are differentiated, mTORC1 is important for lipogenesis and the chronic absence of mTORC1 activity (by *Raptor* ablation) results in lipodistrophic mice (41, 42). Gain of function studies (via tissue-specific *Tsc1* knockout) of mTORC1 in adipocytes resulted in increased *in vitro* palmitate esterification in inguinal adipose tissue (43). In our adipocyte *Tsc1* knockout model, we were surprised that there were no obvious increases in lipogenic enzymes in the mammary gland, in spite of increased milk fat composition. This is consistent with data from *Raptor* knockout adipocytes which have elevated (not decreased) ACC, ACLY, and FASN protein levels (41). We propose two potential explanations, one is that there is increased peripheral lipid synthesis, which is then transported to the mammary gland adipocytes for storage and secretion. This is consistent with elevated expression of the fatty acid transporter *Fabp4* (Figure 6C). Further studies using depot-specific activation of mammary adipocytes will be important to separate the roles of peripheral adipocytes from mammary adipocytes with respect to lactation.

Transgenic activation of Akt (an upstream activator of mTORC1) in mammary epithelial cells resulted in higher milk fat percentage during lactation and larger milk lipid droplet size compared to the control mice (44). In a separate study, supplementation of the mTORC1 activating branched chain amino acid valine increased mammary gland lipogenic activity during lactation in a way that was reversible by the mTORC1 inhibitor rapamycin (45). Together these data suggest that mTORC1 activation may positively regulate milk lipids through multiple cell-types. We found that the secreted milk volume measured at PND10.5 was similar across genotypes. This suggests that the main driver of the modestly increased pup weight could be the increase in milk fat percentage.

In addition to total lipids, we show an increase in both the relative desaturation of lipids, and the levels of DHA in milk of adipocyte *Tsc1* knockout mice. DHA is an essential ω-3 fatty acid important for infant growth and development and has been linked to improved cognitive performance, psychomotor development, and visual acuity (46–48). DHA and EPA levels are highly variable in human milk, and a better understanding of the physiological signals that control DHA levels in milk is important to optimizing the delivery of essential lipids to the infant. We examined the expression of the PC-DHA transporter *Mfsd2a* (49) but did not detect any differences in our mammary gland expression data. The DHA levels may also be linked to our observation of reduced gene expression of markers of adaptive immune cells. We show that several enzymes that convert DHA into bioactive lipids, are upregulated in our lysates (Figure 6E). DHA-derived eicosanoids such as D-series resolvins and protectins could serve as negative signals to reduce the number of B and T cells in the mammary gland. This in turn could affect both mammary gland morphology, but also the secretion of antibodies into the expressed milk.

This is the first report that adipocyte mTORC1 activation alters the lipids in milk, and provides important new data towards our understanding of lipid metabolism during a critical developmental window. There are several strengths of our approach, including the use of matched diets, single parity (to avoid de- and re-differentiation concerns) and normalized litter sizes to comprehensively evaluate milk lipids and mammary gene expression. However, there are several limitations to this approach including the inability to exclude *in utero* effects on offspring growth, the inability to separate the roles of peripheral and mammary adipocyte depots, and the lack of a clear mechanism by which mammary (or peripheral) adipocytes result in increased milk lipids, milk fat saturation and milk DHA levels.

Our data show that elevations in mTORC1 activity in adipocytes of pregnant and lactating dams can impact milk composition, offspring weight, and mammary gland gene expression and morphology. These findings are crucial to better understand the effects of nutrient sensing in the mammary gland on milk production and offspring health. These data support our hypothesis that mTORC1 activation in adipocytes increases the capacity to produce fat and secrete it into the milk. The mechanisms by which mTORC1 could be influencing mammary gland function and milk secretion will be helpful in addressing the effects of maternal excess nutrient signaling on lactation and infant health.

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# Author Contributions

This study was conceptualized by NEH, DB and BG. Resources and funding were provided by BG and DB. The project was administered by DB and NEH. Investigation was performed by NEH, ACM, HH, JRR, ZC, and MCM. Formal analyses, computation, testing and visualizations were performed by NEH, ACM and DB. Data was curated by NEH. The initial draft was written by NEH and DB, with all authors reviewing and approving of the final version.

# References

1. Products - Data Briefs - Number 392 - November 2020. [online] https://www.cdc.gov/nchs/products/databriefs/db392.htm (Accessed April 6, 2021).

2. Barker, D. J. P. 2007. The origins of the developmental origins theory. *J. Intern. Med.* **261**: 412–417. [online] http://doi.wiley.com/10.1111/j.1365-2796.2007.01809.x (Accessed April 1, 2019).

3. Ramji, N., J. Quinlan, P. Murphy, and J. M. G. Crane. 2016. The Impact of Maternal Obesity on Breastfeeding. *J. Obstet. Gynaecol. Canada*. **38**: 703–711. [online] http://www.ncbi.nlm.nih.gov/pubmed/27638980 (Accessed May 15, 2019).

4. Rasmussen, K. M., and C. L. Kjolhede. 2004. Prepregnant overweight and obesity diminish the prolactin response to suckling in the first week postpartum. *Pediatrics*. **113**: e465-71.

5. Bider-Canfield, Z., M. P. Martinez, X. Wang, W. Yu, M. P. Bautista, J. Brookey, K. A. Page, T. A. Buchanan, and A. H. Xiang. 2017. Maternal obesity, gestational diabetes, breastfeeding and childhood overweight at age 2 years. *Pediatr. Obes.* **12**: 171–178. [online] http://doi.wiley.com/10.1111/ijpo.12125 (Accessed July 21, 2019).

6. Castillo, H., I. S. Santos, and A. Matijasevich. 2016. Maternal pre-pregnancy BMI, gestational weight gain and breastfeeding. *Eur. J. Clin. Nutr.* **70**: 431–436. [online] http://www.nature.com/articles/ejcn2015232 (Accessed May 24, 2019).

7. Bzikowska-Jura, A., A. Czerwonogrodzka-Senczyna, G. Olędzka, D. Szostak-Węgierek, H. Weker, and A. Wesołowska. 2018. Maternal Nutrition and Body Composition During Breastfeeding: Association with Human Milk Composition. *Nutrients*. **10**. [online] http://www.ncbi.nlm.nih.gov/pubmed/30262786 (Accessed May 24, 2019).

8. De La Garza Puentes, A., A. M. Alemany, A. M. Chisaguano, R. M. Goyanes, A. I. Castellote, F. J. Torres-Espínola, L. García-Valdés, M. Escudero-Marín, M. T. Segura, C. Campoy, and M. C. López-Sabater. 2019. The effect of maternal obesity on breast milk fatty acids and its association with infant growth and cognition-The PREOBE follow-up. *Nutrients*. **11**. [online] /pmc/articles/PMC6770754/ (Accessed April 6, 2021).

9. Macias, H., and L. Hinck. 2012. Mammary gland development. *Wiley Interdiscip. Rev. Dev. Biol.* **1**: 533–57. [online] http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC3404495 (Accessed June 24, 2019).

10. Hartmann, P. E., R. A. Owens, D. B. Cox, and J. C. Kent. 1996. Establishing lactation Breast development and control of milk synthesis.

11. Landskroner-Eiger, S., J. Park, D. Israel, J. W. Pollard, and P. E. Scherer. 2010. Morphogenesis of the developing mammary gland: stage-dependent impact of adipocytes. *Dev. Biol.* **344**: 968–78. [online] http://www.ncbi.nlm.nih.gov/pubmed/20599899 (Accessed July 17, 2019).

12. Machino, M. 1976. Growth and Differentiation, Vo1. [online] https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1440-169X.1976.00079.x (Accessed July 17, 2019).

13. Zwick, R. K., M. C. Rudolph, B. A. Shook, B. Holtrup, E. Roth, V. Lei, A. Van Keymeulen, V. Seewaldt, S. Kwei, J. Wysolmerski, M. S. Rodeheffer, and V. Horsley. 2018. Adipocyte hypertrophy and lipid dynamics underlie mammary gland remodeling after lactation. *Nat. Commun.* **9**: 3592. [online] http://www.ncbi.nlm.nih.gov/pubmed/30181538 (Accessed July 10, 2019).

14. Catalán, V., J. Gómez-Ambrosi, A. Rodríguez, B. Ramírez, P. Andrada, F. Rotellar, V. Valentí, R. Moncada, P. Martí, C. Silva, J. Salvador, and G. Frühbeck. 2015. Expression of S6K1 in human visceral adipose tissue is upregulated in obesity and related to insulin resistance and inflammation. *Acta Diabetol.* **52**: 257–266. [online] http://link.springer.com/10.1007/s00592-014-0632-9 (Accessed July 19, 2019).

15. Cai, H., L. Q. Dong, and F. Liu. 2016. Recent Advances in Adipose mTOR Signaling and Function: Therapeutic Prospects. *Trends Pharmacol. Sci.* **37**: 303–317. [online] http://www.ncbi.nlm.nih.gov/pubmed/26700098 (Accessed July 19, 2019).

16. Wang, X., and C. G. Proud. 2006. The mTOR Pathway in the Control of Protein Synthesis. *Physiology*. **21**: 362–369. [online] http://www.ncbi.nlm.nih.gov/pubmed/16990457 (Accessed July 19, 2019).

17. Catania, C., E. Binder, and D. Cota. 2011. mTORC1 signaling in energy balance and metabolic disease. *Int. J. Obes.* **35**: 751–761. [online] http://www.nature.com/articles/ijo2010208 (Accessed July 19, 2019).

18. Laplante, M., and D. M. Sabatini. 2009. An Emerging Role of mTOR in Lipid Biosynthesis. *Curr. Biol.* **19**: R1046–R1052. [online] http://www.ncbi.nlm.nih.gov/pubmed/19948145 (Accessed July 25, 2019).

19. Qin, Z., H. Zheng, L. Zhou, Y. Ou, B. Huang, B. Yan, Z. Qin, C. Yang, Y. Su, X. Bai, J. Guo, and J. Lin. 2016. Tsc1 deficiency impairs mammary development in mice by suppression of AKT, nuclear ERα, and cell-cycle-driving proteins. *Sci. Rep.* **6**: 1–10. [online] www.nature.com/scientificreports (Accessed May 12, 2021).

20. Rezaei, R., Z. Wu, Y. Hou, F. W. Bazer, and G. Wu. 2016. Amino acids and mammary gland development: nutritional implications for milk production and neonatal growth. *J. Anim. Sci. Biotechnol.* **7**: 20. [online] http://www.ncbi.nlm.nih.gov/pubmed/27042295 (Accessed July 10, 2019).

21. Kwiatkowski, D. J., H. Zhang, J. L. Bandura, K. M. Heiberger, M. Glogauer, N. el-Hashemite, and H. Onda. 2002. A mouse model of TSC1 reveals sex-dependent lethality from liver hemangiomas, and up-regulation of p70S6 kinase activity in Tsc1 null cells. *Hum. Mol. Genet.* **11**: 525–534. [online] http://expmed.bwh.harvard.edu/ts/review/ (Accessed May 12, 2021).

22. Eguchi, J., X. Wang, S. Yu, E. E. Kershaw, P. C. Chiu, J. Dushay, J. L. Estall, U. Klein, E. Maratos-Flier, and E. D. Rosen. 2011. Transcriptional control of adipose lipid handling by IRF4. *Cell Metab.* **13**: 249–259. [online] /pmc/articles/PMC3063358/ (Accessed May 12, 2021).

23. Wang, F., S. E. Mullican, J. R. DiSpirito, L. C. Peed, and M. A. Lazar. 2013. Lipoatrophy and severe metabolic disturbance in mice with fat-specific deletion of PPARγ. *Proc. Natl. Acad. Sci. U. S. A.* **110**: 18656–18661. [online] http://www.pnas.org/cgi/doi/10.1073/pnas.1314863110 (Accessed July 15, 2019).

24. Wang, Z. V., Y. Deng, Q. A. Wang, K. Sun, and P. E. Scherer. 2010. Identification and characterization of a promoter cassette conferring adipocyte-specific gene expression. *Endocrinology*. **151**: 2933–2939. [online] /pmc/articles/PMC2875825/ (Accessed May 12, 2021).

25. Wang, Q. A., A. Song, R. K. Gupta, B. Deplancke, and P. E. Scherer. 2018. Reversible De-differentiation of Mature White Adipocytes into Preadipocyte-like Precursors during Lactation. *Cell Metab.* **28**: 282-288.e3. [online] https://doi.org/10.1016/j.cmet.2018.05.022 (Accessed July 10, 2019).

26. Boston, W. S., G. T. Bleck, J. C. Conroy, M. B. Wheeler, and D. J. Miller. 2001. Short Communication: Effects of Increased Expression of α-Lactalbumin In Transgenic Mice on Milk Yield and Pup Growth. American Dairy Science Association. [online] https://www.journalofdairyscience.org/article/S0022-0302(01)74516-X/pdf (Accessed June 19, 2019).

27. Collares, F. P., C. V. Gonçalves, and J. S. Ferreira. 1997. Creamatocrit as a rapid method to estimate the contents of total milk lipids. *Food Chem.* **60**: 465–467. [online] https://www.sciencedirect.com/science/article/pii/S0308814697000149 (Accessed February 19, 2020).

28. Patro, R., G. Duggal, M. I. Love, R. A. Irizarry, and C. Kingsford. 2017. Salmon provides fast and bias-aware quantification of transcript expression. *Nat. Methods*. **14**: 417–419.

29. Love, M. I., C. Soneson, P. F. Hickey, L. K. Johnson, N. Tessa Pierce, L. Shepherd, M. Morgan, and R. Patro. 2020. Tximeta: Reference sequence checksums for provenance identification in RNA-seq. *PLoS Comput. Biol.* **16**: 1–13.

30. Soneson, C., M. I. Love, and M. D. Robinson. 2016. Differential analyses for RNA-seq: Transcript-level estimates improve gene-level inferences [version 2; referees: 2 approved]. *F1000Research*. **4**: 1–23.

31. Love, M. I., W. Huber, and S. Anders. 2014. Moderated estimation of fold change and dispersion for RNA-seq data with DESeq2. *Genome Biol.* **15**: 550.

32. MontpellierRessourcesImagerie. 2020. Adipocytes Tools.

33. R: The R Project for Statistical Computing. [online] https://www.r-project.org/ (Accessed May 12, 2021).

34. Bates, D., M. Mächler, B. Bolker, and S. Walker. 2014. No Title. *ArXiv e-prints*. **arXiv:1406**. [online] http://arxiv.org/abs/1406.5823 (Accessed August 13, 2019).

35. Ballard, O., and A. L. Morrow. 2013. Human Milk Composition. Nutrients and Bioactive Factors. *Pediatr. Clin. North Am.* **60**: 49–74. [online] /pmc/articles/PMC3586783/?report=abstract (Accessed August 22, 2020).

36. Kim, J. E., and J. Chen. 2004. Regulation of peroxisome proliferator-activated receptor-γ activity by mammalian target of rapamycin and amino acids in adipogenesis. *Diabetes*. **53**: 2748–2756. [online] https://diabetes.diabetesjournals.org/content/53/11/2748 (Accessed May 11, 2021).

37. Cho, H. J., J. Park, H. W. Lee, Y. S. Lee, and J. B. Kim. 2004. Regulation of adipocyte differentiation and insulin action with rapamycin. *Biochem. Biophys. Res. Commun.* **321**: 942–948.

38. Yeh, W.-C., B. E. Bierert, and S. L. Mcknightt. 1995. Rapamycin inhibits clonal expansion and adipogenic differentiation of 3T3-L1 cells.

39. Huynh, H. D., W. Wei, and Y. Wan. 2017. mTOR Inhibition Subdues Milk Disorder Caused by Maternal VLDLR Loss. *Cell Rep.* **19**: 2014–2025.

40. Namba, R., L. J. T. Young, C. K. Abbey, L. Kim, P. Damonte, A. D. Borowsky, J. Qi, C. G. Tepper, C. L. MacLeod, R. D. Cardiff, and J. P. Gregg. 2006. Rapamycin inhibits growth of premalignant and malignant mammary lesions in a mouse model of ductal carcinoma in situ. *Clin. Cancer Res.* **12**: 2613–2621. [online] www.aacrjournals.org (Accessed May 11, 2021).

41. Lee, P. L., Y. Tang, H. Li, and D. A. Guertin. 2016. Raptor/mTORC1 loss in adipocytes causes progressive lipodystrophy and fatty liver disease. *Mol. Metab.* **5**: 422–432. [online] /pmc/articles/PMC4877665/ (Accessed April 27, 2021).

42. Polak, P., N. Cybulski, J. N. Feige, J. Auwerx, M. A. Rüegg, and M. N. Hall. 2008. Adipose-Specific Knockout of raptor Results in Lean Mice with Enhanced Mitochondrial Respiration. *Cell Metab.* **8**: 399–410.

43. Magdalon, J., P. Chimin, T. Belchior, R. X. Neves, M. A. Vieira-Lara, M. L. Andrade, T. S. Farias, A. Bolsoni-Lopes, V. A. Paschoal, A. S. Yamashita, A. J. Kowaltowski, and W. T. Festuccia. 2016. Constitutive adipocyte mTORC1 activation enhances mitochondrial activity and reduces visceral adiposity in mice. *Biochim. Biophys. Acta - Mol. Cell Biol. Lipids*. **1861**: 430–438.

44. Schwertfeger, K. L., J. L. McManaman, C. A. Palmer, M. C. Neville, and S. M. Anderson. 2003. Expression of constitutively activated Akt in the mammary gland leads to excess lipid synthesis during pregnancy and lactation. *J. Lipid Res.* **44**: 1100–12. [online] http://www.ncbi.nlm.nih.gov/pubmed/12700340 (Accessed July 17, 2019).

45. Che, L., M. Xu, K. Gao, C. Zhu, L. Wang, X. Yang, X. Wen, H. Xiao, Z. Jiang, and D. Wu. 2019. Valine increases milk fat synthesis in mammary gland of gilts through stimulating AKT/MTOR/SREBP1 pathway†. *Biol. Reprod.* **101**: 126–137. [online] https://academic.oup.com/biolreprod/article/101/1/126/5462648 (Accessed April 27, 2021).

46. Helland, I. B., L. Smith, B. Blomen, K. Saarem, O. D. Saugstad, and C. A. Drevon. 2008. Effect of supplementing pregnant and lactating mothers with n-3 very-long-chain fatty acids on children’s iq and body mass index at 7 years of age. *Pediatrics*. **122**: e472–e479. [online] www.pediatrics.org/cgi/doi/10.1542/ (Accessed May 11, 2021).

47. Jensen, C. L., R. G. Voigt, T. C. Prager, Y. L. Zou, J. K. Fraley, J. C. Rozelle, M. R. Turcich, A. M. Llorente, R. E. Anderson, and W. C. Heird. 2005. Effects of maternal docosahexaenoic acid intake on visual function and neurodevelopment in breastfed term infants. *Am. J. Clin. Nutr.* **82**: 125–132. [online] https://academic.oup.com/ajcn/article/82/1/125/4863316 (Accessed May 11, 2021).

48. Birch, E. E., S. E. Carlson, D. R. Hoffman, K. M. Fitzgerald-Gustafson, V. L. N. Fu, J. R. Drover, Y. S. Castañeda, L. Minns, D. K. H. Wheaton, D. Mundy, J. Marunycz, and D. A. Diersen-Schade. 2010. The DIAMOND (DHA Intake and Measurement of Neural Development) Study: A double-masked, randomized controlled clinical trial of the maturation of infant visual acuity as a function of the dietary level of docosahexaenoic acid. *Am. J. Clin. Nutr.* **91**: 848–859. [online] www.cdc.gov/growthcharts/ (Accessed May 12, 2021).

49. Nguyen, L. N., D. Ma, G. Shui, P. Wong, A. Cazenave-Gassiot, X. Zhang, M. R. Wenk, E. L. K. Goh, and D. L. Silver. 2014. Mfsd2a is a transporter for the essential omega-3 fatty acid docosahexaenoic acid. *Nature*. **509**: 503–506. [online] https://www.nature.com/articles/nature13241 (Accessed May 11, 2021).

# Figure Legends

**Figure 1: Experimental timeline and dam body composition**. (A) Experimental timeline. Dams and pups were monitored throughout lactation. Offspring are born and weighed at PND0.5. Offspring were culled to 4 (2 males, 2 females) on PND2.5. Milk volume determinations were conducted on PND10.5. PND16.5 marks the end of the experiment where the dam and pups are weighed then euthanized, milk is collected from mammary glands of the dam, and mammary glands are excised for histological and molecular studies. Maternal body composition was measured on PND0.5 after delivery and every Monday, Wednesday, and Friday thereafter until and including PND16.5. (B) Schematic showing mammary glands (in teal) and whole body adipocytes for wildtype (in green) and knockout (in red) mice with Tsc1 deletion. (C) Maternal body weights. (D) Maternal lean mass. (E) Maternal fat mass. (F) Maternal change in fat mass postnatally from the day of delivery until PND16.5. (G) Weekly food intake. Asterisks indicate p<0.05 from mixed linear model. (n=11 dams).

**Figure 2: Mammary glands histology.** (A) Inguinal and abdominal mammary gland weights. (B) Histological analysis showing increased number of adipocytes in KO thoracic mammary glands. (C) Average area of the mammary gland comprised of adipocytes. (D) Mean adipocyte area. (E) Distribution of adipocyte area, cumulative over all images. (F) Percent of adipocytes by genotype and area range. For E the asterisk indicates a significantly different distribution of adipocyte sizes by a Kolmogrov-Smirnoff test. (G) Representative image of a WT thoracic mammary gland section. (H) H&E representative image of a KO thoracic mammary gland section. For B and C, mixed linear models were used with images as the random effect and genotype as the fixed effect. (n=8 images per dam, 11 dams total).

**Figure 3: Litter size and pup weight.** (A) Average number of pups born to WT and KO dams per their single litters. (B) Weights of male and female offspring of WT and KO dams at PND7.5. The asterisk indicates effect of maternal genotype from 2x2 ANOVA, # indicates significance within female offspring. (n=44 offspring from 11 dams total).

**Figure 4: Milk fat analysis.** (A) Average fat percent composition of milk from KO dams is higher than fat composition of milk from WT dams (n=21 dams) (B) Lower levels of saturated fatty acids (SFA) in milk of KO. (C) Higher levels of total monounsaturated fatty acids (MUFA) in milk of KO. (D) Higher MUFA/SFA ratio in milk of KO. (E) Similar total PUFA levels in milk of KO and WT. (E) Higher levels of ω-3 fatty acids in milk of KO. (F) Similar levels of ω-6 fatty acids in milk of KO and WT. (G) Lower ω-6:ω-3 ratio in milk of KO. (n=10 dams).

**Figure 5: Transcriptomic analysis of mammary glands.** (A) Heatmap of significantly differentially expressed genes between wild-type and knockout mammary glands. (B) Volcano plot comparing fold change to significance of specific genes. (C) Selected lipogenic gene expression D) Selected PPARg target genes. (E) Selected genes involved in eicosanoid metabolism and signaling. (F) Network map of the top differentially expressed pathways from gene ontology – biological process. Jaccard distances were used to calculate similarity between pathways based on overlapping genes, and those distances are indicated as the edges. Net enrichment score (NES) indicates up or downregulation, while node size indicates the number of genes in that pathway. (G) T- and B-Cell gene expression markers. Asterisks indicate q<0.05, number sign indicates p<0.05.

**Supplementary Figure 1: Offspring weight.** Weight of offspring at birth (PND0.5). (n= 84 offspring from 11 dams).

**Supplementary Figure 2: Milk volume measurement.** (A) Weight gained by pups during 1h refeeding. (B) Weight lost by dam during 1h refeeding. (n=11 dams).

**Supplementary Figure 3: Fatty acid pathways.** ω-3 and ω-6 metabolic pathways, enzymes, and detected ω-3 and ω-6 fatty acids. Fatty acids that were not detected are noted with NA. (n=10 dams).

**Supplementary Table 1: Milk fatty acid composition.** Group mean and standard errors are presented along with the percent change relative to wild-type milk. Test indicates the pairwise test (based on tests of normality and heteroscedasticity) and the resultant p-value.

**Supplementary Table 1: Complete gene expression data.** Gene level expression data including nominal (pvalue) and FDR-adjusted (padj) p-values. NA indicates that the gene was not evaluated by DESeq2, generally due to low expression.

**Supplementary Table 2: Gene set enrichment analyses using gene ontology – biological pathways.** Gene-ontology pathways that reached statistical significance. NES indicates the net enrichment score with positive indicating upregulation of the pathway. Core enrichment indicates the specific genes that drive significance of this pathway.