Maternal Obesity Enhances Oocyte Chromosome Abnormalities Associated With Aging

Yan Yun^{1,2}, Zijie Wei², and Neil Hunter^{1,2,3,4†}

¹Howard Hughes Medical Institute, University of California, Davis, Davis, California, USA.

²Department of Microbiology & Molecular Genetics, University of California, Davis, Davis, California, USA.

³Department of Molecular & Cellular Biology, University of California, Davis, Davis, California, USA.

⁴Department of Cell Biology & Human Anatomy, University of California, Davis, Davis, California, USA.

† Correspondence to: Neil Hunter, E-mail: nhunter@ucdavis.edu; Tel: (+1) 530-754-4401

ORCID

N.H. 0000-0003-1498-2327

Y.Y. 0000-0002-8293-0070

Acknowledgments

We thank Richard Shultz and members of the Hunter Lab for support and discussions. N.H. is an Investigator of the Howard Hughes Medical Institute, which also supported this study.

Abstract

Obesity is increasing globally and maternal obesity has adverse effects on pregnancy outcomes and the long-term health of offspring. Maternal obesity has been associated with pregnancy failure through impaired oogenesis and embryogenesis. However, whether maternal obesity causes chromosome abnormalities in oocytes has remained unclear. Here we show that chromosome abnormalities are increased in the oocytes of obese mice and identify weakened sister-chromatid cohesion as the likely cause. Numbers of full-grown follicles retrieved from obese mice were the same as controls and the efficiency of *in vitro* oocyte maturation remained high. However, chromosome abnormalities presenting in both metaphase-I and metaphase-II were elevated, most prominently the premature separation of sister chromatids. Weakened sister-chromatid cohesion in oocytes from obese mice was manifested both as the terminalization of chiasmata in metaphase-I and as increased separation of sister centromeres in metaphase II. Obesity-associated abnormalities were elevated in older mice implying that maternal obesity exacerbates the deterioration of cohesion seen with advancing age.

Keywords: oocyte, meiosis, chromosome, aneuploidy, cohesin, maternal age effect

INTRODUCTION

Aneuploid embryos are a major cause of human infertility, miscarriage and congenital disease (Herbert et al. 2015; Jones and Lane 2013; Nagaoka et al. 2012). A majority of human aneuploidies originate from chromosome segregation errors in the female germline and increase dramatically with advancing maternal age (Chiang et al. 2010; Hodges et al. 2005; Lister et al. 2010; Yun et al. 2014a). This maternal-age effect reflects the deterioration of oocytes during the protracted arrest stage called dictyotene that is peculiar to oogenesis. Oocytes enter meiosis during fetal life, complete chromosome pairing and crossing over, and then arrest around birth. Resumption of meiosis and completion of the first division occurs only in mature oocytes that are about to be ovulated. Thus, an individual human oocyte can remain arrested in dictyotene for ~11 to 50 years, i.e. puberty through menopause.

During the fetal stages of oocyte meiosis, chromosomes are replicated and sorted into homologous pairs, which then recombine to form inter-homolog crossovers (Hunter 2017; Reichman et al. 2017). In combination with cohesion between sister-chromatids, crossovers establish connections called chiasmata. When oocytes resume meiosis, chiasmata play an essential role in homolog disjunction, enabling homolog pairs to stably biorient on the meiosis-I spindle (MacLennan et al. 2015; Watanabe 2012). Homolog disjunction also requires that the two kinetochores of each pair of sister chromatids attach to spindle microtubules emanating from the same pole (mono-orientation) (Hauf et al. 2007; Hirose et al. 2011). At anaphase I, cohesion between the arms of sister chromatids is destroyed to resolve chiasmata and allow homolog disjunction. By contrast, cohesion between sister centromeres must be protected from destruction until anaphase II so that sister chromatids can biorient and disjoin on the meiosis II spindles (Holt and Jones 2009; Kudo et al. 2006).

It is now recognized that deterioration of sister-chromatid cohesion is a major underlying cause of the maternal-age effect (Chiang et al. 2010; Duncan et al. 2012; Lister et al. 2010;

Yun et al. 2014b). Cohesin complexes establish cohesion during meiotic S-phase and early prophase I, but cannot be replenished thereafter I (Burkhardt et al. 2016; Revenkova et al. 2010; Severson and Meyer 2014; Tachibana-Konwalski et al. 2010). Thus, the depletion of cohesion in aging oocytes appears to be irreversible and impacts meiotic chromosome segregation in several ways. With deterioration of arm cohesin, chiasmata loosen causing them to migrate to more terminal positions (chiasma terminalisation), before eventually being lost, negatively impacting the ability of homologs to biorient and disjoin at meiosis I (Imai and Moriwaki 1982; Jagiello and Fang 1979; Kouznetsova et al. 2007; Lacefield and Murray 2007; Nagaoka et al. 2011; Sakuno et al. 2011). When centromeric cohesion is depleted prior to meiosis I, the normally tight association of sister kinetochores is weakened, increasing the risk of aberrant biorientation and equational segregation of sister chromatids at anaphase-I (Angell 1991; Angell et al. 1994; Shomper et al. 2014; Tachibana-Konwalski et al. 2013; Watanabe 2012). Even if sister kinetochores mono-orient and homologs disjoin during meiosis I, diminished centromere cohesion, including failure to protect centromere cohesion from destruction in anaphase I, can cause premature separation of sister centromeres (PSSC) and missegregation in meiosis II (Herbert et al. 2015).

In addition to maternal age, other extrinsic factors can contribute to oocyte segregation errors, including exposure to environmental toxins and being overweight or obese (Hunt et al. 2003; Luzzo et al. 2012; Wang et al. 2011). The effects of overweight and obesity on female reproduction have been studied for decades and are now generally accepted to have adverse impacts on pregnancy outcomes (Broughton and Moley 2017; Jungheim et al. 2010; Lashen et al. 2004; Selesniemi et al. 2011; Zhang et al. 2010). Weight gain and obesity are also generally associated with maternal aging (Goncalves et al. 2017; Pfannenberger et al. 2010). In both humans and mouse, either paternal or maternal obesity can impact embryo development and pregnancy outcome (Binder et al. 2012; Campbell et al. 2015; Finger et al. 2015; Fullston et al. 2015; McPherson et al. 2015), and even the health of offspring via transgenerational inheritance of epigenetic alterations (Ge et al. 2014; Saben et al. 2016;

Watkins et al. 2018; Wu et al. 2015). The lower fertility of obese mothers is believed to derive from reduced oocyte quality because it can be ameliorated via *in vitro* fertilization with donor oocytes from normal weight individuals (Jungheim et al. 2013; Luke et al. 2011). However, other studies argue that obesity is also associated with lower uterine receptivity (Bellver et al. 2010; Bellver et al. 2013).

Mouse models have revealed that obesity can impact oocyte quality in several ways, including lipotoxicity, mitochondrial dysfunction, altered DNA methylation and increased apoptosis (Ge et al. 2014; Han et al. 2018; Jungheim et al. 2010; Saben et al. 2016; Wu et al. 2015; Wu et al. 2010; Zhao et al. 2017). Meiotic abnormalities associated with maternal obesity include defects in spindle morphology and chromosome misalignment (Boots et al. 2016; Han et al. 2017; Luzzo et al. 2012). In later life, obesity can develop into diabetes, and maternal diabetes in mouse has been associated with increased rates of PSSC and aneuploidy (Cheng et al. 2011; Wang et al. 2009).

In the current study, we explore the associations between maternal obesity, chromosome abnormalities and age-dependent exhaustion of cohesion. Our data suggest that obesity exacerbates the maternal-age effect by accelerating cohesin deterioration.

RESULTS

A well-established mouse model of obesity induced by high-fat diet (HFD) (Ge et al. 2014) was employed to investigate the effects of maternal obesity on oocyte quality, focusing on events at the chromosome level. Animals at three and six-months old, fed either HFD or a control diet (CD), defined our four experimental cohorts. Consistent with previous studies (Ge et al. 2014), at three months old, body weights of HFD-fed animals were 44.5% higher than those of controls (**Fig. 1A**; 29.5 ± 6.2 g versus 20.4 ± 1.6 g in CD controls, $P=0.0015$, *t*-test); and by six months HFD animals were 68.8% heavier than controls (**Fig. 1A**; 38.5 ± 4.4 g versus 22.8 ± 2.7 g in CD controls, $P<0.0001$, *t*-test).

Obesity does not affect the efficiency of oocyte maturation

Effects of maternal obesity on oocyte growth and maturation were assessed by: (i) quantifying the numbers of fully grown germinal-vesicle (GV) oocytes retrieved from the ovaries of aged-matched HFD and CD animals; (ii) the efficiency of meiotic resumption when oocytes were cultured *in vitro*, as assessed by GV breakdown (GVBD); and (iii) the efficiency of the meiosis-I division scored by first polar body extrusion (PBE; **Fig. 1B,C,D**).

Surprisingly, there were no significant differences between the numbers of GV-stage oocytes retrieved from any of the four study cohorts. Though variation among individual animals from each group was large, the mean values from all groups were similar, ranging between 23 and 26 GV oocytes per animal (**Fig. 1B**). Contradicting previous analysis (Hou et al. 2016), we detected no effects of maternal obesity on oocyte maturation when cultured *in vitro*. The efficiencies of both GVBD and PBE were indistinguishable for oocytes from HFD and CD animals (**Fig. 1C, D**).

Obesity is associated with chromosome abnormalities in both metaphase I and II of oocyte meiosis

Metaphase chromosome spreads of *in vitro* cultured oocytes were used to assess abnormalities in both MI and MII (**Fig. 2A**). Abnormalities detectable in MI include unconnected univalents caused by either failed crossing over during fetal oogenesis, or premature loss of cohesion between chromosome arms. Univalents are prone to missegregation at anaphase I, either mono-orienting on the MI spindle and disjoining as intact pairs of chromatids (homolog non-disjunction); or becoming bi-oriented and undergoing equational segregation. Consequently, abnormalities detectable in metaphase-II arrested oocytes include numerical abnormalities (aneuploidy) and free chromatids (premature separation of sister centromeres, PSSC).

Both three and six month HFD obesity cohorts showed significantly elevated levels of oocyte chromosome abnormalities relative to CD controls (**Fig. 2B**). 9.1% (2/22) of metaphase-I oocytes from six-month old HFD animals contained univalents compared to 1.4% (1/71) of CD controls, but this difference was not statistically significant at the <5% level ($P=0.14$, fisher's exact test; **Fig. 2C**). Univalents were not detected in three-month old animals, either HFD or CD.

Similarly, in metaphase-II arrested oocytes, aneuploidy was detected at low levels but differences between HFD and CD cohorts were not statistically significant (**Fig. 2D**). However, significant increases in metaphase II oocytes with PSSC were observed in HFD animals (**Fig. 2E**). In three month-old animals, 5.2% (4/77) of metaphase II eggs contained single chromatids, which were never observed in the age-matched CD group (0/115; $P=0.02$, Fisher's exact test). PSSC was even more frequent in six month-old HFD animals, with 12.1% (4/33) oocytes containing single chromatids compared to just 1.0% (1/96) in age-matched controls (**Fig. 2E**). Notably, all nuclei with PSSC contained two free chromatids but were otherwise euploid ($n=40$ chromatids). These abnormalities most likely derive from normal homolog disjunction in MI, accompanied by complete loss of centromere cohesion between a single chromatid pair (Herbert et al. 2015).

Chiasma terminalization is increased in the oocytes of obese animals

Deterioration of sister-chromatid cohesion can lead to univalents in metaphase I, and aneuploidy and PSSC in metaphase II. To investigate whether cohesin deterioration contributes to obesity-related increases in chromosome abnormalities, we analysed the distributions of chiasmata in metaphase-I chromosome spreads (**Fig. 3**). We scored three classes of chiasmata based on the numbers and positions of chiasmata: (i) terminal, with a single end-to-end connection; (ii) interstitial, with a single connection and visible cross-shaped morphology; and (ii) multiple, with two or more connections (**Fig. 3A**).

In oocytes from six-month old animals, the distributions of chiasmata classes were significantly different between the HFD and CD cohorts ($P < 0.05$; G-test). HFD oocytes had elevated levels of terminal chiasmata (32.7% versus 26.3% in CD oocytes, $P < 0.05$, Chi-square test) and corresponding reductions in bivalents with multiple chiasmata (16.0% versus 21.7% in CD oocytes, $P < 0.05$, Chi-square test; **Fig. 3B**). By comparison, distributions of chiasmata classes did not differ between three-month old HFD and CD animals. Thus, maternal obesity appears to accelerate the age-dependent deterioration of cohesin.

Inter-kinetochore distances are increased in metaphase II oocytes of obese animals

Increased terminalization of chiasmata in HFD oocytes of 6-month old animals indicates accelerated deterioration of cohesion between chromosome arms. However, the most prominent chromosomal abnormality observed in HFD oocytes, PSSC, occurs when centromeric cohesion is diminished (Chiang et al. 2010; Yun et al. 2014b).

To assess whether centromere cohesion is weakened in obese mice, inter-kinetochore distances (IKDs) were measured in metaphase-II arrested oocytes (**Fig. 4A**). Analysis of the average IKDs per nucleus showed a trend towards slightly larger IKDs in HFD oocytes from three-month old animals ($1.11 \pm 0.22 \mu\text{m}$ versus $1.04 \pm 0.19 \mu\text{m}$ in CD controls; **Fig. 4B**), but the difference was not significant ($P = 0.24$, Mann-Whitney test). However, the rank distributions of IKDs for individual sister-chromatid pairs indicated significantly larger IKDs in three-month old HFD oocytes ($P = 0.004$, Mann-Whitney test; **Fig. 4C**). At six months, significant increases in IKDs were readily detected in HFD oocytes, both by analysis of average IKDs per nucleus ($1.31 \pm 0.22 \mu\text{m}$ versus $1.10 \pm 0.27 \mu\text{m}$ in CD controls, $P = 0.01$, t -test; **Fig. 4B**) and by the rank distributions ($P < 0.0001$, Mann-Whitney test; **Fig. 4D**). Thus, HFD-induced obesity is also associated with accelerated weakening of centromeric cohesion.

DISCUSSION

In our study, maternal obesity did not affect the numbers of fully-grown GV oocytes produced, or their ability to mature *in vitro* (**Fig. 1B-D**). Similarly, the data of Ata *et al.* showed that Body Mass Index in humans did not affect oocyte yield or *in vitro* maturation (Ata *et al.* 2013). However, conflicting data from human *in vitro* fertilization (IVF) studies have indicated that maternal obesity does negatively impact oocyte yield and maturation (Zhang *et al.* 2010; Zhang *et al.* 2015a). IVF routinely involves long-term administration of gonadotropin to stimulate follicle growth and increase numbers of mature eggs. It is important to note that obese women, who have a higher risk of infertility, show a reduced response to gonadotropin (Ozekinci *et al.* 2015; Zhang *et al.* 2010). Thus, the reduced yield and maturation efficiency of eggs from obese women in an IVF setting could be caused primarily by their decreased response to gonadotropin. Consistently, minimizing ovary stimulation of obese women can negate these effects (Zhang *et al.* 2015a). Importantly, in our mouse study, oocyte growth was not primed with gonadotropin and obese mice yielded normal numbers of healthy oocytes capable of reentering meiosis and completing MI with normal efficiency.

Although obese mice produced normal numbers of oocytes, their quality was reduced at the chromosome level, with enhanced deterioration of cohesion leading to chiasma terminalization, increased IKDs and PSSC. These data complement a previous study (Luzzo *et al.* 2012), which showed an association between maternal obesity, MI spindle defects and chromosome misalignment in mouse oocytes. Importantly, obesity mimics and thereby exacerbates the deterioration of cohesion seen during maternal aging. This observation suggests that obesity and maternal aging could diminish cohesion via similar mechanisms. A possible unifying mechanism of cohesion deterioration is oxidative damage. HFD-induced obesity leads to increased oxidative stress in mouse oocytes (Jia *et al.* 2018; Zhang *et al.* 2015b); and Perkins *et al.* recently showed that genetically-enhancing oxidative stress increases cohesion loss and segregation errors in *Drosophila* oocytes (Perkins *et al.* 2016).

Oxidative stress could damage the cohesins themselves as well as factors directly or indirectly involved in their stability.

PSSC events detected in HFD oocytes, comprising two free chromatids in an otherwise euploid nucleus, are consistent with normal homolog disjunction in MI, followed by dissociation of a single pair of chromatids. Such events could be the consequence of a general deterioration of cohesion during dictyotene, or a more specific but not exclusive failure to protect centromeric cohesion from destruction in anaphase I. The first possibility predicts that HFD oocytes will have increased IKDs in metaphase I, while the latter predicts that only metaphase II oocytes will show significantly increased IKDs and PSSC. Favoring a model in which HFD-induced obesity leads to inefficient protection of centromeric cohesion, we did not detect increases in average IKDs per nucleus in metaphase-I oocytes ($0.53 \pm 0.08 \mu\text{m}$ in HFD-6m versus $0.56 \pm 0.08 \mu\text{m}$ in CD-6m controls, $P=0.31$, t -test).

At the onset of anaphase I, the separase protease is released from inhibition and cleaves specifically phosphorylated cohesin to allow homolog disjunction (Holt and Jones 2009). Centromere-associated cohesin is protected from cleavage by the PP2A phosphatase, which is recruited to centromeres by the Shugoshin protein, Sgo2 (Kitajima et al. 2006). Interestingly, Sgo2 is also reduced with advancing maternal age (Lister et al. 2010; Yun et al. 2014b). Given our observations, we propose that obesity may also lead to diminished Sgo2 levels. In summary, our data provide new insight into the complex effects of obesity on female reproduction, revealing enhanced cohesin deterioration that mimics and compounds the maternal-age effect.

METHODS

Animals and Diet

Original C57BL/6J mice were purchased from the Jackson Lab. Animals were maintained and used for experimentation according to the guidelines of the Institutional Animal Care and

Use Committees of the University of California, Davis. Weanling females (21 days post-partum) were housed 3 or 4 per cage and fed *ad lib*. The mice were fed either a high-fat diet (HFD; Research Diets Inc.; D12492 with 60% kcal% fat) or a standard rodent chow control diet (CD) for 3 or 6 months.

Oocyte collection and *in vitro* maturation

Germinal-vesicle stage oocytes were collected from ovaries of experimental animals without prior hormonal stimulation. Only oocytes with integral cumulus cell layers were utilized. Oocytes were collected in M2 medium under mineral oil at 37°C, and cultured for *in vitro* maturation after mechanically removing surrounding cumulus cells for observation of Germinal Vesicle Breakdown (GVBD) and Polar Body Extrusion (PBE). GVBD was scored after 3 hours of culture. Only oocytes that underwent GVBD within 3 hours were used to quantify PBE after a further 12 hours of incubation.

Chromosome spreads of metaphase I and II oocytes

Metaphase I and II oocytes were acquired after 7 hours and 15 hours of culture in M2 medium at 37°C. Metaphase chromosome spreads were performed as previously described (Qiao et al. 2018). Briefly, Acid Tyrode's solution (Sigma-Aldrich) was applied to remove zona pellucida, and zona-free oocytes were spread in 1% paraformaldehyde with 0.15% Triton-X-100 and 3 Mm DTT in H₂O. To improve the accuracy of chromosome counting, single oocytes were spread in each well of a 12-well slide (Electron Microscopy Science). Spreads were air dried at room temperature overnight.

Immunofluorescence and data analysis

Metaphase I and II oocyte spreads were blocked at room temperature for 1-2 hours, followed by overnight incubation with primary antibody – human anti-centromere antibodies (ACA or CREST; HCT-0100 ImmunoVision, 1:1000). Goat anti-human 555 secondary antibodies (Molecular Probes, 1:1000) were incubated for 1hour at room temperature.

Chromosomes were stained with 4',6-diamidino-2-phenylindole (DAPI). Images were acquired using a Zeiss AxioPlan II microscope equipped with a 63X Plan Apochromat 1.4 objective, EXFO X-Cite metal halide light source with Hamamatsu ORCA-ER CCD camera. Image processing and analysis were performed using Volocity (Perkin Elmer) and ImageJ (NIH) software.

Statistical analysis

Dichotomous data were analysed using Fisher's exact, Chi-squared or *G* tests. All other mean analyses were performed using either the Student's *t* or Mann–Whitney tests. Data were processed using GraphPad Prism, with a significance threshold of $P < 0.05$. In all comparisons, at least two mice (littermates or age-matched) were examined from at least two independent experiments.

REFERENCES

- Angell RR (1991) Predivision in human oocytes at meiosis I: a mechanism for trisomy formation in man *Hum Genet* 86:383-387
- Angell RR, Xian J, Keith J, Ledger W, Baird DT (1994) First meiotic division abnormalities in human oocytes: mechanism of trisomy formation *Cytogenet Cell Genet* 65:194-202 doi:10.1159/000133631
- Ata B, Seyhan A, Al-Shalaty J, Escriva AM, Son WY, Tan SL (2013) Effect of Body Mass Index on In Vitro Maturation Treatment Outcomes in Women without Polycystic Ovarian Syndrome *J IVF Reprod Med Genet* 1 doi:10.4172/2375-4508.1000104
- Bellver J et al. (2010) Female obesity impairs in vitro fertilization outcome without affecting embryo quality *Fertility and Sterility* 93:447-454 doi:10.1016/j.fertnstert.2008.12.032
- Bellver J, Pellicer A, Garcia-Velasco JA, Ballesteros A, Remohi J, Meseguer M (2013) Obesity reduces uterine receptivity: clinical experience from 9,587 first cycles of

- ovum donation with normal weight donors Fertility and Sterility 100:1050-+
doi:10.1016/j.fertnstert.2013.06.001
- Binder NK, Hannan NJ, Gardner DK (2012) Paternal Diet-Induced Obesity Retards Early Mouse Embryo Development, Mitochondrial Activity and Pregnancy Health Plos One 7 doi:ARTN e52304; 10.1371/journal.pone.0052304
- Boots CE, Boudoures A, Zhang W, Drury A, Moley KH (2016) Obesity-induced oocyte mitochondrial defects are partially prevented and rescued by supplementation with co-enzyme Q10 in a mouse model Human Reproduction 31:2090-2097
doi:10.1093/humrep/dew181
- Broughton DE, Moley KH (2017) Obesity and female infertility: potential mediators of obesity's impact Fertil Steril 107:840-847 doi:10.1016/j.fertnstert.2017.01.017
- Burkhardt S et al. (2016) Chromosome Cohesion Established by Rec8-Cohesin in Fetal Oocytes Is Maintained without Detectable Turnover in Oocytes Arrested for Months in Mice Curr Biol 26:678-685 doi:10.1016/j.cub.2015.12.073
- Campbell JM, Lane M, Owens JA, Bakos HW (2015) Paternal obesity negatively affects male fertility and assisted reproduction outcomes: a systematic review and meta-analysis Reprod Biomed Online 31:593-604 doi:10.1016/j.rbmo.2015.07.012
- Cheng PP et al. (2011) Islet transplantation reverses the effects of maternal diabetes on mouse oocytes Reproduction 141:417-424 doi:10.1530/Rep-10-0370
- Chiang T, Duncan FE, Schindler K, Schultz RM, Lampson MA (2010) Evidence that weakened centromere cohesion is a leading cause of age-related aneuploidy in oocytes Curr Biol 20:1522-1528 doi:10.1016/j.cub.2010.06.069
- Duncan FE, Hornick JE, Lampson MA, Schultz RM, Shea LD, Woodruff TK (2012) Chromosome cohesion decreases in human eggs with advanced maternal age Aging Cell 11:1121-1124 doi:10.1111/j.1474-9726.2012.00866.x

- Finger BJ, Harvey AJ, Green MP, Gardner DK (2015) Combined parental obesity negatively impacts preimplantation mouse embryo development, kinetics, morphology and metabolism Human Reproduction 30:2084-2096 doi:10.1093/humrep/dev142
- Fullston T et al. (2015) Female offspring sired by diet induced obese male mice display impaired blastocyst development with molecular alterations to their ovaries, oocytes and cumulus cells J Assist Reprod Gen 32:725-735 doi:10.1007/s10815-015-0470-x
- Ge ZJ et al. (2014) DNA Methylation in Oocytes and Liver of Female Mice and Their Offspring: Effects of High-Fat-Diet-Induced Obesity Environ Health Persp 122:159-164 doi:10.1289/ehp.1307047
- Goncalves LF, Machado TQ, Castro-Pinheiro C, de Souza NG, Oliveira KJ, Fernandes-Santos C (2017) Ageing is associated with brown adipose tissue remodelling and loss of white fat browning in female C57BL/6 mice Int J Exp Pathol 98:100-108 doi:10.1111/iep.12228
- Han LS et al. (2018) Embryonic defects induced by maternal obesity in mice derive from Stella insufficiency in oocytes (vol 50, pg 432, 2018) Nature Genetics 50:768-768 doi:10.1038/s41588-018-0077-0
- Han LS, Wang HC, Li L, Li XY, Ge J, Reiter RJ, Wang Q (2017) Melatonin protects against maternal obesity-associated oxidative stress and meiotic defects in oocytes via the SIRT3-SOD2-dependent pathway J Pineal Res 63 doi:ARTN e12431; 10.1111/jpi.12431
- Hauf S, Biswas A, Langeegger M, Kawashima SA, Tsukahara T, Watanabe Y (2007) Aurora controls sister kinetochore mono-orientation and homolog bi-orientation in meiosis-I EMBO J 26:4475-4486 doi:10.1038/sj.emboj.7601880

- Herbert M, Kalleas D, Cooney D, Lamb M, Lister L (2015) Meiosis and maternal aging: insights from aneuploid oocytes and trisomy births Cold Spring Harb Perspect Biol 7:a017970 doi:10.1101/cshperspect.a017970
- Hirose Y et al. (2011) Chiasmata promote monopolar attachment of sister chromatids and their co-segregation toward the proper pole during meiosis I PLoS Genet 7:e1001329 doi:10.1371/journal.pgen.1001329
- Hodges CA, Revenkova E, Jessberger R, Hassold TJ, Hunt PA (2005) SMC1beta-deficient female mice provide evidence that cohesins are a missing link in age-related nondisjunction Nat Genet 37:1351-1355 doi:10.1038/ng1672
- Holt JE, Jones KT (2009) Control of homologous chromosome division in the mammalian oocyte Mol Hum Reprod 15:139-147 doi:10.1093/molehr/gap007
- Hou YJ, Zhu CC, Duan X, Liu HL, Wang Q, Sun SC (2016) Both diet and gene mutation induced obesity affect oocyte quality in mice Sci Rep 6:18858 doi:10.1038/srep18858
- Hunt PA et al. (2003) Bisphenol a exposure causes meiotic aneuploidy in the female mouse Curr Biol 13:546-553
- Hunter N (2017) Oocyte Quality Control: Causes, Mechanisms, and Consequences Cold Spring Harb Symp Quant Biol 82:235-247 doi:10.1101/sqb.2017.82.035394
- Imai HT, Moriwaki K (1982) A re-examination of chiasma terminalization and chiasma frequency in male mice Chromosoma 85:439-452
- Jagiello G, Fang JS (1979) Analyses of diplotene chiasma frequencies in mouse oocytes and spermatocytes in relation to ageing and sexual dimorphism Cytogenet Cell Genet 23:53-60 doi:10.1159/000131302
- Jia Z et al. (2018) Resveratrol reverses the adverse effects of a diet-induced obese murine model on oocyte quality and zona pellucida softening Food Funct 9:2623-2633 doi:10.1039/c8fo00149a

- Jones KT, Lane SI (2013) Molecular causes of aneuploidy in mammalian eggs *Development* 140:3719-3730 doi:10.1242/dev.090589
- Jungheim ES, Schoeller EL, Marquard KL, Loudon ED, Schaffer JE, Moley KH (2010) Diet-Induced Obesity Model: Abnormal Oocytes and Persistent Growth Abnormalities in the Offspring *Endocrinology* 151:4039-4046 doi:10.1210/en.2010-0098
- Jungheim ES, Schon SB, Schulte MB, DeUgarte DA, Fowler SA, Tuuli MG (2013) IVF outcomes in obese donor oocyte recipients: a systematic review and meta-analysis *Human Reproduction* 28:2720-2727 doi:10.1093/humrep/det292
- Kitajima TS, Sakuno T, Ishiguro K, Iemura S, Natsume T, Kawashima SA, Watanabe Y (2006) Shugoshin collaborates with protein phosphatase 2A to protect cohesin *Nature* 441:46-52 doi:10.1038/nature04663
- Kouznetsova A, Lister L, Nordenskjold M, Herbert M, Hoog C (2007) Bi-orientation of achiasmatic chromosomes in meiosis I oocytes contributes to aneuploidy in mice *Nat Genet* 39:966-968 doi:10.1038/ng2065
- Kudo NR et al. (2006) Resolution of chiasmata in oocytes requires separase-mediated proteolysis *Cell* 126:135-146 doi:10.1016/j.cell.2006.05.033
- Lacefield S, Murray AW (2007) The spindle checkpoint rescues the meiotic segregation of chromosomes whose crossovers are far from the centromere *Nat Genet* 39:1273-1277 doi:10.1038/ng2120
- Lashen H, Fear K, Sturdee DW (2004) Obesity is associated with increased risk of first trimester and recurrent miscarriage: matched case-control study *Hum Reprod* 19:1644-1646 doi:10.1093/humrep/deh277
- Lister LM et al. (2010) Age-related meiotic segregation errors in mammalian oocytes are preceded by depletion of cohesin and Sgo2 *Curr Biol* 20:1511-1521 doi:10.1016/j.cub.2010.08.023

- Luke B, Brown MB, Stern JE, Missmer SA, Fujimoto VY, Leach R, Grp ASW (2011) Female obesity adversely affects assisted reproductive technology (ART) pregnancy and live birth rates *Human Reproduction* 26:245-252 doi:10.1093/humrep/deq306
- Luzzo KM et al. (2012) High fat diet induced developmental defects in the mouse: oocyte meiotic aneuploidy and fetal growth retardation/brain defects *PLoS One* 7:e49217 doi:10.1371/journal.pone.0049217
- MacLennan M, Crichton JH, Playfoot CJ, Adams IR (2015) Oocyte development, meiosis and aneuploidy *Semin Cell Dev Biol* 45:68-76 doi:10.1016/j.semcdb.2015.10.005
- McPherson NO, Bell VG, Zander-Fox DL, Fullston T, Wu LL, Robker RL, Lane M (2015) When two obese parents are worse than one! Impacts on embryo and fetal development *Am J Physiol-Endoc M* 309:E568-E581 doi:10.1152/ajpendo.00230.2015
- Nagaoka SI, Hassold TJ, Hunt PA (2012) Human aneuploidy: mechanisms and new insights into an age-old problem *Nat Rev Genet* 13:493-504 doi:10.1038/nrg3245
- Nagaoka SI, Hodges CA, Albertini DF, Hunt PA (2011) Oocyte-specific differences in cell-cycle control create an innate susceptibility to meiotic errors *Curr Biol* 21:651-657 doi:10.1016/j.cub.2011.03.003
- Ozekinci M et al. (2015) Does obesity have detrimental effects on IVF treatment outcomes? *BMC Womens Health* 15:61 doi:10.1186/s12905-015-0223-0
- Perkins AT, Das TM, Panzera LC, Bickel SE (2016) Oxidative stress in oocytes during midprophase induces premature loss of cohesion and chromosome segregation errors *Proc Natl Acad Sci U S A* 113:E6823-E6830 doi:10.1073/pnas.1612047113
- Pfannenberger C et al. (2010) Impact of Age on the Relationships of Brown Adipose Tissue With Sex and Adiposity in Humans *Diabetes* 59:1789-1793 doi:10.2337/db10-0004

- Qiao H et al. (2018) Impeding DNA Break Repair Enables Oocyte Quality Control *Mol Cell* 72:211-221 e213 doi:10.1016/j.molcel.2018.08.031
- Reichman R, Alleva B, Smolikove S (2017) Prophase I: Preparing Chromosomes for Segregation in the Developing Oocyte *Results Probl Cell Differ* 59:125-173 doi:10.1007/978-3-319-44820-6_5
- Revenkova E, Herrmann K, Adelfalk C, Jessberger R (2010) Oocyte cohesin expression restricted to preantral stages provides full fertility and prevents aneuploidy *Curr Biol* 20:1529-1533 doi:10.1016/j.cub.2010.08.024
- Saben JL et al. (2016) Maternal Metabolic Syndrome Programs Mitochondrial Dysfunction via Germline Changes across Three Generations *Cell Rep* 16:1-8 doi:10.1016/j.celrep.2016.05.065
- Sakuno T, Tanaka K, Hauf S, Watanabe Y (2011) Repositioning of aurora B promoted by chiasmata ensures sister chromatid mono-orientation in meiosis I *Dev Cell* 21:534-545 doi:10.1016/j.devcel.2011.08.012
- Selesniemi K, Lee HJ, Muhlhauser A, Tilly JL (2011) Prevention of maternal aging-associated oocyte aneuploidy and meiotic spindle defects in mice by dietary and genetic strategies *Proc Natl Acad Sci USA* 108:12319-12324 doi:10.1073/pnas.1018793108
- Severson AF, Meyer BJ (2014) Divergent kleisin subunits of cohesin specify mechanisms to tether and release meiotic chromosomes *Elife* 3:e03467 doi:10.7554/eLife.03467
- Shomper M, Lappa C, FitzHarris G (2014) Kinetochore microtubule establishment is defective in oocytes from aged mice *Cell Cycle* 13:1171-1179 doi:10.4161/cc.28046
- Tachibana-Konwalski K, Godwin J, Borsos M, Rattani A, Adams DJ, Nasmyth K (2013) Spindle assembly checkpoint of oocytes depends on a kinetochore structure

determined by cohesin in meiosis I Curr Biol 23:2534-2539
doi:10.1016/j.cub.2013.10.052

Tachibana-Konwalski K, Godwin J, van der Weyden L, Champion L, Kudo NR, Adams DJ, Nasmyth K (2010) Rec8-containing cohesin maintains bivalents without turnover during the growing phase of mouse oocytes Genes Dev 24:2505-2516
doi:10.1101/gad.605910

Wang Q, Ratchford AM, Chi MMY, Schoeller E, Frolova A, Schedl T, Moley KH (2009) Maternal Diabetes Causes Mitochondrial Dysfunction and Meiotic Defects in Murine Oocytes Mol Endocrinol 23:1603-1612 doi:10.1210/me.2009-0033

Wang ZB, Schatten H, Sun QY (2011) Why is chromosome segregation error in oocytes increased with maternal aging? Physiology (Bethesda) 26:314-325
doi:10.1152/physiol.00020.2011

Watanabe Y (2012) Geometry and force behind kinetochore orientation: lessons from meiosis Nat Rev Mol Cell Biol 13:370-382 doi:10.1038/nrm3349

Watkins AJ et al. (2018) Paternal diet programs offspring health through sperm- and seminal plasma-specific pathways in mice P Natl Acad Sci USA 115:10064-10069
doi:10.1073/pnas.1806333115

Wu LL et al. (2015) Mitochondrial dysfunction in oocytes of obese mothers: transmission to offspring and reversal by pharmacological endoplasmic reticulum stress inhibitors Development 142:681-691 doi:10.1242/dev.114850

Wu LLY, Dunning KR, Yang X, Russell DL, Lane M, Norman RJ, Robker RL (2010) High-Fat Diet Causes Lipotoxicity Responses in Cumulus-Oocyte Complexes and Decreased Fertilization Rates Endocrinology 151:5438-5445 doi:10.1210/en.2010-0551

- Yun Y, Holt JE, Lane SI, McLaughlin EA, Merriman JA, Jones KT (2014a) Reduced ability to recover from spindle disruption and loss of kinetochore spindle assembly checkpoint proteins in oocytes from aged mice *Cell Cycle* 13:1938-1947 doi:10.4161/cc.28897
- Yun Y, Lane SI, Jones KT (2014b) Premature dyad separation in meiosis II is the major segregation error with maternal age in mouse oocytes *Development* 141:199-208 doi:10.1242/dev.100206
- Zhang D et al. (2010) Overweight and obesity negatively affect the outcomes of ovarian stimulation and in vitro fertilisation: a cohort study of 2628 Chinese women *Gynecol Endocrinol* 26:325-332 doi:10.3109/09513591003632100
- Zhang JJ, Feret M, Chang L, Yang M, Merhi Z (2015a) Obesity adversely impacts the number and maturity of oocytes in conventional IVF not in minimal stimulation IVF *Gynecol Endocrinol* 31:409-413 doi:10.3109/09513590.2015.1014785
- Zhang L et al. (2015b) Sirt3 prevents maternal obesity-associated oxidative stress and meiotic defects in mouse oocytes *Cell Cycle* 14:2959-2968 doi:10.1080/15384101.2015.1026517
- Zhao LH, Lu TF, Gao L, Fu XW, Zhu SE, Hou YP (2017) Enriched endoplasmic reticulum-mitochondria interactions result in mitochondrial dysfunction and apoptosis in oocytes from obese mice *J Anim Sci Biotechnol* 8 doi:ARTN 62; 10.1186/s40104-017-0195-z

Figure 1: Obesity does not affect oocyte maturation

(A) Body weights of 3-month (3m) and 6-month (6m) old experimental animals (mean $\pm$ s.d.). (B) Numbers of GV oocytes retrieved per animal (mean $\pm$ s.d.). (C and D) Proportions of oocytes undergoing GVBD (C) and PBE (D). Numbers of oocytes analysed are indicated in parentheses. Data were analysed using the Student's t-test (A and B) or Fisher's exact test (C and D). **, $P < 0.01$; ****, $P < 0.0001$; ns, not significant.

Figure 2: Chromosome abnormalities are increased in oocytes from obese mice

(A) Representative images of chromosome abnormalities detected in metaphase-I and metaphase-II chromosome spreads. Left to right: metaphase-I oocyte with 19 bivalents and 1 pair of univalents (yellow arrows); aneuploid metaphase-II oocyte with 21 dyads; euploid metaphase-II oocyte with PSSC (yellow arrows highlight free chromatids; images in the red rectangle are from the same cell, but represent different fields of view). Kinetochores (CREST) are red, chromosomes (DAPI) are grey. Scale bars, 10 μ m. (B–E) Quantification of (B) all oocytes with chromosome abnormalities; (C) metaphase-I oocytes with univalents; (D) aneuploid metaphase-II oocytes; (E) metaphase-II oocytes with PSSC. Numbers of oocytes analysed are indicated in parentheses. *, $P < 0.05$; **, $P < 0.01$; ns, not significant; Fisher's exact test.

Figure 3: Chiasma terminalisation is increased in metaphase I oocytes of obese mice

(A) Representative images of bivalents with terminal, interstitial and multiple chiasmata. Chiasma positions are highlighted with yellow caretts. (B) Chiasma distributions. Numbers in the sub-bars show the percentage of each chiasma class. Numbers of bivalents analysed are indicated in parentheses. *, $P < 0.05$; ns, not significant; G-test for distributions, Chi-square test for pairwise comparisons.

Figure 4: Inter-kinetochore distances are increased in metaphase II oocytes from obese mice

(A) Representative chromosome spread of a metaphase II oocyte. A single dyad is enlarged to highlight the IKD measurement. Kinetochores (CREST) are red, chromosomes (DAPI) are grey. Scale bars represent 10 μm (nucleus) or 1 μm (dyad). (B) Average IKDs per nucleus. Bars show means $\pm$ s.d. of all nuclei. (C, D) Rank distributions of the IKDs of individual dyads. *, $P < 0.05$; **, $P < 0.01$; ****, $P < 0.0001$; ns, not significant; Student's t -test (6m group in B); Mann-Whitney test (3m group in B, C, D).