Initial spindle formation at the oocyte center protects against incorrect kinetochore-microtubule attachment and aneuploidy in mice

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ABSTRACT

Aneuploidy is the leading genetic cause of miscarriage and infertility in women and occurs frequently in oocytes. Spindle formation and positioning are two critical events that must be regulated tightly to avoid erroneous chromosome segregation. Following nuclear envelope breakdown (NEBD), the spindle is assembled centrally before migrating towards the cortex to allow the first asymmetric division. The biological significance of the primary central positioning of the spindle is unknown. Because the spindle forms where NEBD occurs, whether positioned at the center or at the cortex of the cell, full-grown GV (prophase I) oocytes were collected from CF-1 mice (6-8 weeks old) and sorted according to the position of the GV into three groups: central, intermediate, and peripheral. Approximately 50% of the cells exhibited a central GV position, while 25% of cells showed a peripheral GV position. These proportions were similar to those obtained by histological evaluation of ovarian oocytes in 6-8 week mice, but not to those of mice aged less than 5 weeks, which tended to have a majority of peripherally positioned GVs. When peripheral GV oocytes were matured *in vitro*, GVs (88%) migrated towards the center and NEBD (and spindle assembly) occurred either at the center of the cell or during migration. The percentages of NEBD and polar body (PB) extrusion did not vary significantly among groups. Importantly, peripheral GV oocytes had a significant increase of abnormal K-MT attachments at metaphase I (Met I) and showed a significant increase of aneuploidy at metaphase II (Met II) when compared to central GV oocytes. Interestingly, peripheral GV oocytes that were able to achieve full GV relocation to the center were half as likely to experience aneuploidy when compared to peripheral GV oocytes unable to achieve relocation. These results indicate that preferential central spindle formation is an insurance mechanism to protect against incorrect K-MT attachments and aneuploidy.

INTRODUCTION

Infertility is an extremely prevalent issue worldwide, affecting approximately 122 million women worldwide (Sun, et al., 2019). The leading genetic cause of infertility is aneuploidy and can be characterized as errors within chromosomal segregation (Jacobs, et al., 1959, Lejeune, et al., 1959). Fertility and aneuploidy demonstrate an inversely correlated relationship throughout the lifetime of a female, with the highest incidence of aneuploidy occurring at the lowest rate of fertility (Gruhn, et al., 2019). Aneuploidy often causes failure to fertilize, miscarriage, spontaneous abortion, congenital defects *in vivo* (ex: down syndrome), and is the leading contributor to *in vitro* fertilization failure (Angell, et al., 1986, Byrne, et al., 1985, Gruhn, Zielinska, Shukla, Blanshard, Capalbo, Cimadomo, Nikiforov, Chan, Newnham, Vogel, Scarica, Krapchev, Taylor, Kristensen, Cheng, Ernst, Bjorn, Colmorn, Blayney, Elder, Liss, Hartshorne, Grondahl, Rienzi, Ubaldi, McCoy, Lukaszuk, Andersen, Schuh and Hoffmann, 2019, Hassold and Hunt, 2001). Aneuploidy more commonly arises in female gametes (eggs) than in male gametes (Hassold and Hunt, 2001), and from mistakes during Meiosis I (MI) than they do in MII (Hassold, et al., 2007). Therefore, as the average maternal age increases, so does the risk of infertility and aneuploidy; it is crucial to understand basic mechanisms regulating female meiosis I.

Oogenesis is a complex process that begins during fetal development in female mammalian species, shortly after conception. During the third trimester of pregnancy, oogonia enter meiosis I (MI) and duplicate their chromosomes (Gilbert, 2000). Shortly after birth, all germ cells undergo a prolonged arrest that is maintained until puberty. Hormonal stimulation during ovulation causes the oocytes to resume meiosis (Gilbert, 2000). In full-grown prophase I oocytes, the

germinal vesicle (GV) localizes mainly at the center (Brunet and Maro, 2007). *In vitro*, peripherally localized GV migrates towards the cortex, regulated by F-actin. The network of filamentous actin within the oocyte, more dense at the cortex and less dense at the center due to gradients of GTPases (Azoury, et al., 2008), relocates the GV centrally through gentle movement governed by active diffusion, rather than exerting a force on the GV (Almonacid, et al., 2015). However, why the GV relocates to the center of the oocyte remains unknown.

Upon meiotic resumption, prophase I oocytes undergo nuclear envelope breakdown (NEBD). Throughout the NEBD process, the microtubule organizing centers (MTOCs) undergo a three-step fragmentation before clustering and sorting into two dominant spindle poles that are integral in forming a bipolar spindle at the center of the oocyte in Met I (Schuh and Ellenberg, 2007). The spindle dictates the plane of cell division (McCarthy and Goldstein, 2006), and therefore must migrate to the cortex of the oocyte to ensure the highly asymmetric meiotic division (Longo and Chen, 1985, McCarthy and Goldstein, 2006). Extruding a small polar body through a highly asymmetrical division is critical as it allows the egg to retain a majority of the cytoplasmic store of maternal RNAs and proteins synthesized during the growth phase which are essential to fertilization and early embryonic development (Ma, et al., 2006, Menezo, 2006). Once again, however, the biological significance of primary central formation and positioning of the spindle prior to its cortical migration is unknown.

Given that the spindle forms where NEBD occurs (Balboula, et al., 2016, Balboula, et al., 2015), we sorted full-grown GV oocytes according to the positioning of the GV into three groups: central, intermediate, and peripheral. We used these models as a tool to study the biological significance of central spindle formation and positioning. Here we show that GV positioning is a

47 dynamic process that depends on maternal age, mice aged 6-8 weeks maintain a majority of
48 centrally positioned GV oocytes, and that peripheral GV positioning is associated with increased
49 chromosome misalignment, incorrect kinetochore-microtubule (K-MT) attachments and
50 aneuploidy. Importantly, allowing peripherally positioned GV oocytes to relocate the GV to the
51 center, significantly decreased the rate of aneuploidy. Our results are the first to demonstrate that
52 preferential central spindle formation and its positioning at the center of the oocyte are critical to
53 establish correct K-MT attachments and protect against aneuploidy in mammalian oocytes.
54

55 # RESULTS

56 ***GV Positioning – A dynamic process***

57 Because the spindle forms where NEBD occurs (Balboula, Nguyen, Gentilello, Quartuccio,
58 Drutovic, Solc and Schindler, 2016, Balboula, Stein, Schultz and Schindler, 2015), we sorted
59 full-grown GV oocytes according to the positioning of the GV into three groups: central,
60 intermediate, and peripheral; from here out, these groups were referred to as containing central
61 GV oocytes, intermediate GV oocytes, or peripheral GV oocytes (Fig. 1A). Peripheral GV
62 oocytes had a distance of 5 µm or less from the GV to the nearest cortex, intermediate GV
63 oocytes remained a distance of 5 to 15 µm from the GV to the nearest cortex, and central GV
64 oocytes maintained more than 15 µm distance from the GV to the nearest cortex (Fig. 1A,B).
65 First, we observed the proportions of these groups of oocytes *in vitro.* Oocytes with a centrally
66 located germinal vesicle were the most prevalent, nearly 47.34% of all oocytes collected.
67 Oocytes with intermediately positioned GV accounted for nearly 27.75% of all collected oocytes,
68 while peripheral oocytes represented only 24.91% of collected cells (Fig. 1C,D).

69 To determine whether GV positioning proportions *in vitro* are similar to those *in vivo*, ovaries
70 were collected at four ages (2 weeks, 3 weeks, 5 weeks, and 8 weeks) in order to display GV
71 positioning throughout sexual development. All oocytes and their corresponding GV positioning
72 were examined from histological sections of ovary stained with Hematoxylin and Eosin (Fig.
73 1E,F). Similar to our *in vitro* results, ovaries from mice aged 8 weeks showed a majority of
74 oocytes with centrally positioned GVs (65.98%). Interestingly, younger mice (2 & 3 weeks of
75 age) showed a majority of peripherally located GV (50.46% and 55.63%, respectively)
76 respectively, while mice aged 5 weeks showed very similar proportions of oocytes with both
77 centrally and peripherally located GVs (42.86% and 43.25%, respectively) (Figure 1.F,G),
78 suggesting that, before sexual maturation, oocytes have eccentrically positioned GVs (likely
79 incompetent) prior to their central relocation after sexual maturation.
80
81 ***Oocytes with cortically located GV associate with higher rates of chromosome misalignment***
82 ***and aneuploidy***
83 Upon meiotic resumption, the germinal vesicle (GV) undergoes nuclear envelope breakdown
84 (NEBD) and is shortly followed by the formation of a bipolar spindle and the alignment of
85 chromosomes at the metaphase plate. Peripheral GV positioning increases with maternal age and
86 correlates with decreased maturation rate (Brunet, 2007). To assess the meiotic progression,
87 oocytes were collected from 6-8 weeks old mice and matured for 16 h (Met II). The majority
88 (~92%) of centrally located GV oocytes were able to successfully undergo NEBD. On the other
89 hand, peripherally located GV oocytes showed a significant decrease in the percentage of
90 successful NEBD (~61%) (Figure 2A). However, using time-lapse microscopy, we found no
91 significant difference in the timing of NEBD between centrally located GV oocytes and

92 peripherally located GV oocytes (Figure 2B). Similarly, a majority of centrally located GV
93 oocytes were able to undergo successful polar body extrusion (PBE, ~81%), while peripherally
94 located GV oocytes demonstrated a tendency to be less successful to extrude the first PB (~59%,
95 Fig. 2C). Once again, there was no significant difference in the time of PBE when both centrally
96 located GV oocytes and peripherally located GV oocytes were compared (Fig. 2D).
97 To assess the spindle morphology and chromosome alignment among the groups, oocytes were
98 matured *in vitro* for either 7 h (Met I) or 16 h (Met II), fixed, and immunostained with α-tubulin
99 to label the spindle and stained with DAPI to label the DNA. Interestingly, we found a
100 significant increase in the percentage of chromosome misalignment either at Met I or Met II in
101 oocytes with more peripherally positioned GV when compared to centrally located ones.
102 Intermediate GV oocytes also showed significantly higher rates of chromosome misalignment
103 when compared to central GV oocytes in Met I, but not at Met II (Fig. 2E,F,H,I). Chromosome
104 alignment was assessed according to the parameters previously described by (Lane, et al., 2012).
105 On the other hand, spindle morphology did not vary significantly among groups in both Met I
106 and Met II oocytes (Fig. 2E,G,H,J). Because chromosome misalignment is highly associated
107 with aneuploidy, we then assessed aneuploidy in Met II eggs using *in situ* chromosome counting.
108 Strikingly, segregation errors occurred in oocytes with peripherally located GV (~50.15%)
109 nearly 5 times more frequently than oocytes with a centrally located GV (~10.37%, Fig. 2K,L).
110

111 ***Nuclear envelope breakdown occurs during central relocation of peripherally located GV***

112 To understand the behavior of the GV and its positioning within the meiotic process, we
113 employed time-lapse microscopy to image the oocytes live every 10 min (Fig. 3A). Interestingly,
114 the GV favors central movement prior to NEBD, as previously reported in (Almonacid, et al.,

115 2014, Sanfins, et al., 2003, Sanfins, et al., 2004). When peripheral GV oocytes were arrested at
116 prophase I by milrinone, a phosphodiesterase inhibitor, only 12.33% of the oocytes remained
117 peripheral after overnight incubation, while the majority (87.67%) relocated to the center of the
118 oocyte (Fig. 3B). When the oocytes were allowed to mature in milrinone-free medium,
119 chromosomes that were initially positioned more peripherally (GV) remained closer to the cortex
120 than intermediately and centrally located ones at the time of chromosome misalignment (Fig.
121 3C). It is of note that the timing of chromosome misalignment did not vary significantly among
122 groups (Fig. 3D). The distance from the GV to the nearest cortex was also measured at NEBD.
123 Notably, the GV which was initially located at the peripheral of the cell underwent 10 ± 1.256
124 μm movement towards the center before the oocyte aligns its chromosomes. Intermediately
125 located GV and centrally located GV underwent central movement and traveled a distance of 6 ±
126 0.6024 μm and 4 ± 0.6783 μm, respectively before chromosome alignment (Fig. 3E). Why
127 oocytes favor central GV positioning is not yet known.
128
129 ***Incorrect kinetochore-microtubule attachments are increased in oocytes with peripherally***
130 ***located germinal vesicle***
131 One important cause of aneuploidy is a weakened or non-functional spindle assembly checkpoint
132 (SAC). Typically, the SAC is inactivated when microtubules are attached correctly to all
133 kinetochores, but a weakened or non-functional SAC may allow the progression of the cell to
134 anaphase and telophase without proper K-MT attachments, a phenomenon that is highly
135 associated with aneuploidy. To assess the SAC function in oocytes with a central, intermediate,
136 or peripheral GV, oocytes were treated with nocodazole, a MT depolymerizing agent that is
137 known to maintain the SAC active and thereby prevent PBE by inducing Met I arrest.

138 Expectedly, positive control oocytes treated by ZM447439, an Aurora Kinase B/C inhibitor that
139 is known to disrupt the SAC function at a high dose (10μM), extruded the PB even in the
140 presence of nocodazole (Lane, et al., 2010). In contrast to ZM447439 treated oocytes, all oocytes
141 (central, intermediate and peripheral) failed to extrude a PB in the presence of nocodazole,
142 suggesting that the SAC is intact and functional (Fig. 4A).
143 Because improper K-MT attachment is another major contributor of aneuploidy and because
144 cortically facing centromeres have relatively high rates of unstable K-MT attachments (Akera, et
145 al., 2017), we hypothesized that early spindle formation and its positioning in the center of the
146 oocyte is required to protect against a cortical influence that may hinder correct K-MT
147 attachments. Even if the SAC is satisfied by KMT attachment, it is not necessary that all
148 attachments are correct and homologous chromosomes are bioriented. To assess K-MT
149 attachments, Met I oocytes were (~7 h) were exposed to a brief cold shock (6 minutes) to
150 depolymerize liable unattached MTs and maintain stable MT fibers that are attached to
151 kinetochores, immunostained, and imaged using confocal microscopy. An α-tubulin antibody
152 was used to label MTs and CREST was used to label kinetochores. K-MT attachments were
153 scored as normal, unattached, or abnormally attached (merotelic or syntelic) (Fig. 4B). GV
154 positioning had no effect on the percentage of unattached kinetochores among all groups (Fig.
155 4B,C). Importantly, oocytes with peripherally located GV displayed ~ four-fold increase in the
156 percentage of incorrect K-MT attachments, compared to oocytes with centrally located GV (Fig.
157 4B-D). Moreover, the percentages of peripheral (37.93 ± 9.17%) and intermediate (39.13 ±
158 10.41%) oocytes having two or more abnormally attached kinetochores were significantly higher
159 than those in the central group (7.14 ± 4.02%). These results suggest that improper K-MT

160 attachments are the likely cause of increased aneuploidy in oocytes with a peripherally located
161 GV (Fig. 4F).
162
163 ***Allowing for central GV relocation partially rescues chromosome mis-segregation***
164 To confirm that the cortical influence during spindle formation is the cause, at least partially, of
165 the high rate of aneuploidy in peripherally located GV oocytes, we tracked the movement of the
166 GV live using time-lapse microscopy. Oocytes with a peripherally located GV demonstrated one
167 of three types of movement: oocytes that were able to achieve complete relocation of the GV to
168 the center were termed 'corrected', oocytes that demonstrated central movement prior to NEBD
169 but did not achieve full relocation were termed 'migratory', and oocytes that failed to make a
170 relocation attempt and remained at the cortex were termed 'peripheral' (Fig. 5A,B). Strikingly,
171 oocytes that were able to successfully relocate their GVs to the center showed rates of
172 aneuploidy similar to those of oocytes beginning with a central GV. On the other hand, oocytes
173 that failed to attempt GV relocation and underwent NEBD at the periphery of the cell continued
174 to experience high levels of aneuploidy, suggesting that the spindle must form and position at the
175 center of the oocyte initially to avoid cortical influence detrimental to the fidelity of establishing
176 K-MT attachments (Fig. 5C).
177
178 **DISCUSSION**
179 Spindle formation and its positioning are two critical events that must be regulated tightly to
180 avoid erroneous chromosome segregation. Upon meiotic resumption and shortly after NEBD, the
181 spindle is assembled and remains at the center of the oocyte prior to its migration towards the
182 cortex. The biological significance of primary spindle formation and its positioning at the center

183 of the oocyte has not been studied. Prophase I oocytes were collected and sorted according to the
184 position of the GV into three groups: central, intermediate, and peripheral. Here we show that the
185 majority of oocytes in the ovaries of sexually mature mice (~ 6-8-weeks old) had a centrally
186 localized GV, whereas mice aged less than 5 weeks had a majority of peripherally positioned
187 GVs in their ovaries. Because the spindle is assembled where NEBD occurs, we took the
188 advantage of the aforementioned observation and compared the consequences when the spindle
189 is formed at the center (central GV oocyte), at the cortex (peripheral GV oocyte) or in between
190 (intermediate GV oocyte). Although we did not find a significant difference in the rate of PBE
191 among groups, peripheral GV oocytes showed a significant decrease in the percentage of NEBD
192 and a significant increase in chromosome misalignment, abnormal K-MT attachments, and
193 aneuploidy when compared to central GV oocytes. Importantly, peripheral GV oocytes that were
194 able to relocate their GVs to the center showed significantly lower levels of aneuploidy when
195 compared to peripheral GV oocytes that were unable to relocate their GVs to the center. These
196 results suggest that primary spindle formation and its positioning in the center of the oocyte are
197 critical to allow proper K-MT attachments and to prevent against the development of aneuploid
198 gametes.
199
200 Abnormal K-MT attachments during Met I is a major cause of aneuploidy in mammalian oocytes
201 (Lane, et al., 1999, Orr, et al., 2015). Our results that peripheral GV oocytes, in which the spindle
202 formed and positioned near the cortex during prometaphase I, had significantly higher rates of
203 abnormal K-MT attachments at Met I and aneuploidy at Met II when compared to those in
204 central GV oocytes, suggest that the cortical signals may have an influence on the ability of the
205 oocyte to establish correct K-MT attachments. Indeed, recent evidence suggests that cortical

206 signals have the capability to influence spindle asymmetry (Akera, Chmatal, Trimm, Yang,
207 Aonbangkhen, Chenoweth, Janke, Schultz and Lampson, 2017). In addition, cortical polarization
208 of the spindle (and following asymmetrical tyrosination) can lead to a non-mendelian selection
209 of stronger centromeres (higher kinetochore protein). In cases where the weaker centromere is
210 located on the central side of the spindle, the K-MT attachments are degraded and reform to
211 bring the stronger centromere towards the center of the cell. Importantly, peripheral GV oocytes
212 that displayed a correction mechanism by relocating their GVs to the center (before spindle
213 assembly) had a significant decrease in the percentage of abnormal K-MT attachments when
214 compared to uncorrected oocytes. Taken together, these findings suggest that primary spindle
215 formation and positioning in the center of the oocyte may serve as an essential protection
216 mechanism against cortical signals capable of influencing improper K-MT attachments.
217
218 Germinal vesicle positioning is often studied only *in vitro* or at a single time point *in vivo* and is
219 thus not very well understood. There has been a long-standing debate regarding the position of
220 the GV in mammalian oocytes. For example, a previous study found that the majority of
221 prophase I-arrested oocytes have peripherally located GVs, and this cortical positioning of the
222 GV is likely influenced by gap junctions and increased cumulus cell contact (Barrett and
223 Albertini, 2010). On the other hand, other studies demonstrated that the majority of prophase I-
224 arrested oocytes have centrally positioned GVs (Almonacid, et al., 2019, Brunet and Maro, 2007,
225 Levi, et al., 2013). Interestingly, in the first study (Barrett and Albertini, 2010), the oocytes were
226 collected from mice aged 21 days, whereas in the other studies (Almonacid, Al Jord, El-Hayek,
227 Othmani, Coulpier, Lemoine, Miyamoto, Grosse, Klein, Piolot, Mailly, Voituriez, Genovesio
228 and Verlhac, 2019, Brunet and Maro, 2007, Levi, Ghetler, Shulman and Shalgi, 2013), the

229 oocytes were collected from mice aged above 8-week old. Our results that the majority of
230 oocytes collected from 2-3-week old mice exhibited a peripherally located GVs and that the
231 majority of oocytes collected from 6-8-week old mice exhibited a centrally located GVs clearly
232 explained the previous findings and add greater clarity to the field. However, why and how GV
233 positioning is a dynamic process during oocyte development remains unknown. During oocyte
234 meiosis, prophase I-arrested oocytes have a cytoplasmic mesh of F-actin vesicles that experience
235 increased movement near the cortex and decreased movement near the center (Almonacid, Terret
236 and Verlhac, 2014). Accordingly, the gradient of F-actin creates a gentle force that encourages
237 the GV to position in the center of the cell through active diffusion (Almonacid, et al., 2018).
238 Analyzing the cytoskeletal changes within the oocyte during its development and growth may
239 reveal more insight into the underlying mechanisms behind GV positioning throughout
240 oogenesis.
241
242 Current *in vitro* fertilization (IVF) technologies maintain much room for improvement, as only
243 12.7% of naturally ovulated IVF cycles in humans produce a pregnancy and only 8.8% of those
244 pregnancies result in live births (Nargund, et al., 2001). Although technologies and protocols
245 have advanced since the first IVF birth in 1978, the success rate in producing a live birth in
246 women under the age of 35 through IVF remains less than 50% (Technology, 2019). To date,
247 there are no definitive morphological markers of predictive oocyte quality and successful IVF
248 that are particularly non-invasive (Rienzi, et al., 2011). Understanding the association between
249 peripherally located GV and the incidence of aneuploidy may allow for the selection of oocytes
250 predisposed to correct segregation of chromosomes. Additionally, arresting the cell and enabling
251 the GV to relocate to central positioning may be a promising approach to increase the overall

252 efficacy of IVF practices, allowing for increases in blastocyst rate, pregnancy rate, and live birth
253 rate in all species.
254

255 MATERIAL AND METHODS

256 *Ethics*

257 All laboratory animals were managed, and experiments conducted, in compliance with the
258 University of Missouri (Animal Care Quality Assurance Reference Number, 9695).
259

260 *Oocyte collection and* in vitro *maturation (IVM)*

261 Full-grown GV oocytes were collected from CF-1 female mice aged 6-8 weeks. Oocyte
262 collection and culture were carried out as previously described (Balboula and Schindler, 2014,
263 Stein and Schindler, 2011). Cumulus oocyte complexes (COCs) were collected and cultured in
264 bicarbonate-free minimal essential medium (MEM) supplemented with 3mg/ml
265 polyvinylpyrrolidone (PVP) and 25 mM Hepes (pH 7.3) under mineral oil (MilliporeSigma, St.
266 Louis, MO, USA # M4659, # P2307, # H3784, # M8410). Oocytes were manually denuded and
267 sorted into 3 groups: Central GV, Intermediate GV, Peripheral GV. Careful rolling of the oocyte
268 ensured correct classification. Oocytes were then transferred to Chatot, Ziomek, and Bavister
269 (CZB) medium (Chatot, et al., 1989) supplemented with 1µM glutamine (MilliporeSigma, #
270 G8549) under mineral oil and matured at 37˚C with humidified 5% CO_2 in an incubator for either
271 7, 14, or 16 h.
272 Nocodazole (Sigma #M1404) and ZM447439 (Tocris #2458) were dissolved in dimethyl
273 sulfoxide (DMSO) and added to CZB culture medium at a final concentration of 5µm and 10µm,
274 respectively.

275 ***Immunocytochemistry***

276 After maturation, oocytes were fixed in a freshly prepared solution of 2.5% (kinetochore
277 experiments) or 3.7% (morphology experiments) paraformaldehyde (MilliporeSigma, # P6148)
278 dissolved in phosphate buffer saline (PBS). Oocytes were incubated in permeabilization solution
279 (0.1% Triton X-100 in PBS) for 20 minutes and blocking solution (0.3% BSA and 0.01%
280 Tween-20 in PBS) for 20 minutes before staining. Oocytes were incubated at room temperature
281 for one h with the primary antibody before undergoing 3 consecutive washes in blocking solution
282 for 9 minutes each. Oocytes were then incubated at room temperature for one h in the secondary
283 antibody solution. Following another 3 consecutive washes in blocking solution at 9 minutes
284 each, oocytes were mounted on glass slides using Vectashield containing 4',6-Diamidino-2-
285 Phenylindole, Dihydrochloride (DAPI; Vector Laboratories, Burlingame, CA, USA) in order to
286 stain the DNA. Fluorescence was observed using a 40X oil objective using a Leica DMI8
287 microscope and oocytes were imaged using 3 µm Z-intervals. Oocytes were analyzed using NIH
288 ImageJ software (National Institute of Health, Bethesda, MD USA).
289 The following primary antibodies were used in immunofluorescence: conjugated α-tubulin-
290 AlexaFluor 488 (Life Technologies # 322 588; 1:75), CREST autoimmune serum (Antibodies
291 Incorporated # 15-234; 1:25).
292

293 ***In situ chromosome counting***

294 Oocytes matured *in vitro* for 14 h in CZB medium supplemented with L-glutamine under mineral
295 oil were transferred to CZB containing 100 µm monastrol (MilliporeSigma, # M8515) and
296 incubated an extra 2 h; monastrol is an Eg5-kinesin inhibitor which induces monopolar spindle
297 formation and thus results in a rosette of chromosome distribution (Balboula and Schindler,

298 2014, Duncan, et al., 2009). After treatment with monastrol, oocytes at Met II stage were fixed in
299 a freshly prepared solution of 2.5% paraformaldehyde (MilliporeSigma, # P6148) and stained
300 with CREST autoimmune serum (Antibodies Incorporated # 15-234; 1:25) to label the
301 kinetochores. DAPI was used to label the DNA. Fluorescence was observed using a 40X oil
302 objective using a Leica DMI8 microscope and oocytes were imaged using 0.5 µm Z-intervals in
303 order to observe all kinetochores. Oocytes were analyzed individually and were scored either as
304 euploid (containing 40 kinetochores) or as aneuploid (containing ± 40 kinetochores).
305
306 ***Assessment of kinetochore-microtubule attachment***
307 Cells were matured *in vitro* for 7 h in CZB medium supplemented with L-glutamine under
308 mineral oil. The oocytes were placed on ice for 6 minutes in a 96 well dish containing chilled
309 MEM. Exposing the oocytes to cold shock depolymerizes unattached MTs; however, when MTs
310 have established end-on attachment to a kinetochore, it becomes cold stable (Rieder, 1981).
311 Oocytes were fixed using a freshly prepared 2.5% paraformaldehyde solution and
312 immunostained with anti-human CREST (to label kinetochores) and α-tubulin (to label MTs)
313 antibodies. DAPI was used to label DNA. Cells were imaged using a Leica TCS SP8 confocal
314 microscope and a x63 oil objective, taking images at 0.5 µm Z-intervals. Kinetochores were
315 analyzed for unattached, normal, or abnormal attachments (syntelic - both kinetochores attached
316 to one side of the spindle or merotelic - a kinetochore maintaining attachment to both sides of the
317 spindle). Oocytes were analyzed using NIH ImageJ Software.
318
319
320

321 ***Time-lapse microscopy***

322 Full-grown oocytes collected from CF-1 mice aged 6-8 weeks were imaged once every 30
323 minutes over time using a 40X oil objective on a Leica DMI8 microscope within a
324 microenvironmental chamber maintaining an atmosphere of 5% CO_2 and temperature of 37˚C in
325 humidified air. DIC imaging acquisition began before NEBD, capturing images at 5 µm Z-
326 intervals with minimal light exposure and intensity. Image sequences were analyzed using NIH
327 ImageJ Software.

328

329 ***Oocyte histology***

330 Ovaries from CF-1 mice of varying ages (2 weeks, 3 weeks, 5 weeks, and 8 weeks) were
331 collected, submerged, and stored in buffered zinc formalin overnight. Tissues were then moved
332 to 70% ethanol for storage until undergoing a 10-h protocol using a Leica ASP300S enclosed
333 tissue processor. After processing, tissues were embedded in paraffin wax and cooled fully using
334 the Leica EG1150 C/H pair. Embedded tissues were sectioned at 8 µm thickness using a Leica
335 Histocore AutoCut microtome. Representative samples were taken for each age by taking 3
336 consecutive sections periodically (every 4, 6, 8, or 10 sections respectively). Tissues were
337 stained with Hematoxylin and Eosin (ABCAM, # 245880) before being mounted with permount
338 resin (Thermo Fisher Scientific, Inc. # SP15). Oocytes and their corresponding GV positioning
339 were examined using a 10X objective on a Leica DMI8 microscope.

340

341 ***Statistical analysis***

342 Tests used to evaluate the statistical significance of the findings reported include One-way
343 ANOVA, Student t-test, and chi-square contingency testing within GraphPad Prism. The Tukey

post hoc test was utilized to determine statistical significance between groups. P values of < 0.05 were considered significant. All data are displayed as means ± SEM.

Declaration of interest

All authors declare that there are no conflicts of interest that may prejudice or bias the research reported.

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Figure Legends

Figure 1: Germinal vesicle positioning is a dynamic process throughout the development

(A) Full-grown oocytes were collected, imaged and classified into one of three groups: central germinal vesicle (GV), intermediate GV, or peripheral GV according to the distance measured from the GV to the nearest cortex (B) Quantification of the average distance from the GV to the nearest cortex within groups established in “A”. One-way ANOVA and Tukey’s post hoc test

367 were performed to analyze the data. (C) Representative images of oocytes with a central,
368 intermediate, and peripherally located GV. The scale bars represent 100 µm. (D) Quantification
369 of the contribution of each group to all oocytes as collected in "C". One-way ANOVA and
370 Tukey's post hoc test were performed to analyze the data. (E) Histological analysis of GV
371 positioning *in vivo* at different ages. Ovaries from 2, 3, 5, and 8 weeks old mice were collected,
372 fixed, and stained with Hematoxylin and Eosin. Sections were observed through 10X and 40X
373 objective magnification and classified into one of the three positioning groups: central,
374 intermediate, peripheral. The scale bar represents 100 µm. (F) Representative images of GV
375 positioning in 3 and 8 weeks old mice. The white box emphasizes the location of the magnified
376 image within the ovary. The scale bar represents 100 µm. (G) Quantification of the proportion of
377 oocytes sorted according to their GV positioning (central, intermediate, peripheral) in 2, 3, 5, and
378 8 week old mice. Two-way ANOVA and Sidak's multiple comparison test were performed to
379 determine if the groups differed significantly. Data are displayed as mean ± SEM. Values with
380 asterisks vary significantly, * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, **** $P < 0.0001$. The total
381 number of analyzed oocytes (from at least 3 independent replicates) is specified above each
382 graph.
383
384 **Figure 2: Oocytes with a peripherally located germinal vesicle have higher rates of**
385 **chromosome misalignment and aneuploidy.**
386 Full-grown prophase I oocytes were collected and sorted into central, intermediate and peripheral
387 groups based on germinal vesicle (GV) positioning and imaged live using time-lapse microscopy
388 during *in vitro* maturation for 16 h (Met II). (A) Quantification of the percentage of oocytes
389 underwent NEBD. (B) Quantification of the average time of NEBD. (C) Quantification of the

390 percentage of first polar body extrusion (1st PBE). (D) Quantification of the average time of
391 PBE. (E-J) Full-grown prophase I oocytes were collected and sorted into central, intermediate
392 and peripheral groups based on GV positioning and *in vitro* matured for 7 h (Met I) or 16 h (Met
393 II. Oocytes were fixed and immunostained with a-tubulin to label the spindle. DNA was labeled
394 by DAPI. (E) Representative confocal images of Met I oocytes. (F) Quantification of the
395 percentage of chromosome misalignment in Met I oocytes. (G) Quantification of the percentage
396 of abnormal spindle morphology in Met I oocytes. (H) Representative confocal images of Met II
397 oocytes. (I) Quantification of the percentage of chromosome misalignment in Met II oocytes. (J)
398 Quantification of the percentage of abnormal spindle morphology in Met II oocytes. (K) Full-
399 grown prophase I oocytes were collected and sorted into central, intermediate and peripheral
400 groups based on GV positioning and *in vitro* matured for 14 h (Met II). Oocytes were fixed and
401 immunostained with CREST antibody to label kinetochores. DNA was labeled by DAPI.
402 Oocytes were analyzed individually and scored either as euploid (containing 40 kinetochores) or
403 as aneuploid (containing ± 40 kinetochores). Shown are representative images. (L)
404 Quantification of the percentage of aneuploid eggs. The scale bar represents 10 μm. One-way
405 ANOVA and Tukey's post hoc tests were performed to determine statistical significance among
406 groups. Data are displayed as mean ± SEM. Values with asterisks vary significantly, * $P < 0.05$,
407 ** $P < 0.01$, *** $P < 0.001$. The total number of analyzed oocytes (from at least 3 independent
408 replicates) is specified above each graph.
409
410
411

412 **Figure 3: Cortically located germinal vesicle favor central movement, but experience**
413 **NEBD during relocation**

414 (A) Representative images of time-lapse microscopy of the movement of peripherally located
415 germinal vesicle (GV) during prophase I arrest. Images were taken every 10 minutes using a Z-
416 interval of 0.5 µm (see Supplemental Movie 1). The black circle identifies the initial GV
417 position, while the green circle identifies the final GV position. The scale bar represents 50 µm.
418 (B) Quantification of the percentage of GV relocation to a central position in intermediate and
419 peripheral oocytes. (C-F) Full-grown prophase I oocytes were collected and sorted into central,
420 intermediate and peripheral groups based on germinal vesicle (GV) positioning and imaged live
421 using time-lapse microscopy during *in vitro* maturation. (C) Quantification of the change in the
422 distance of GV to the nearest cortex (from the initial position at the GV stage to the final
423 destination at NEBD). (D) Quantification of the change in the distance of chromosomes to the
424 cortex (from NEBD until all chromosomes aligned). (E) Quantification of the average time of
425 chromosome alignment. (F) Quantification of the change in the distance of chromosomes to the
426 cortex (from the initial position at the GV stage to the final destination when chromosomes
427 aligned). Alignment, and PBE. One-way ANOVA and Tukey's post hoc test were performed to
428 determine statistical significance. Data are displayed as mean ± SEM. Values with asterisks vary
429 significantly, * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, **** $P < 0.0001$. The total number of
430 analyzed oocytes (from at least 3 independent replicates) is specified above each graph.

431

432

433

434 **Figure 4: Oocytes with peripherally located germinal vesicle experience higher levels of**
435 **incorrect kinetochore-microtubule attachments**
436 (A) Full-grown prophase I oocytes were collected and sorted into central, intermediate and
437 peripheral groups based on germinal vesicle (GV) positioning followed by *in vitro* maturation in
438 milrinone-free medium in the presence of nocodazole. Randomly selected oocytes were *in vitro*
439 matured in the presence of nocodazole and ZM447439 (positive control group). The percentage
440 of polar body extrusion (PBE) was assessed at 16 h (Met II). (B) Representative images of
441 kinetochore-microtubule attachments in oocytes with a central, intermediate, or peripherally
442 located GV. Panels on the right (from top to bottom) display normal K-MT attachment,
443 unattached kinetochores and abnormal K-MT attachment. (C) Quantification of the percentage of
444 unattached kinetochores, normal K-MT attachments (D), and abnormal K-MT attachments (E).
445 (F) Quantification of the oocytes with 2 or more incorrect K-MT attachments. One-way ANOVA
446 and Tukey's post hoc test were performed to analyze the data. Data are displayed as mean ±
447 SEM. Values with asterisks vary significantly, * $P < 0.05$, ** $P < 0.01$, **** $P < 0.0001$. The total
448 number of analyzed oocytes (from at least 3 independent replicates) is specified above each
449 graph.
450
451 **Figure 5: Relocation of the germinal vesicle decreases the incidence of aneuploidy in**
452 **peripheral germinal vesicle oocytes**
453 (A) Schematic depicting the determination of corrected, migratory, and peripheral oocytes. (B)
454 Full-grown oocytes with peripherally located germinal vesicle (GV) were collected and imaged
455 live during *in vitro* maturation using time-lapse microscopy. (B) Representative images of the
456 GV movement prior to NEBD. Images were taken every 30 minutes (Z-interval of 5 μm) to

457 minimize light exposure and intensity. The black circle denotes the primary GV positioning,
458 while the green circle denotes the final GV position prior to NEBD. (C) Quantification of the
459 incidence of aneuploidy in metaphase II oocytes from the oocytes categorized in B. One-way
460 ANOVA and Tukey's post hoc test were performed to determine any statistical significance.
461 Data are displayed as mean ± SEM. Values with asterisks vary significantly, * $P < 0.05$. The total
462 number of analyzed oocytes (from at least 3 independent replicates) is specified above each
463 graph.
464
465 **Supplementary Movie 1:** Time-lapse microscopy of germinal vesicle (GV) oocytes cultured in
466 milrinone-containing medium to induce prophase I arrest. DIC images were captured every 10
467 minutes at Z-intervals of 5 µm. The scale bar represents 50 µm.
468
469 **Supplementary Movie 2:** Time-lapse microscopy of peripheral germinal vesicle (GV) oocyte
470 showing corrected GV relocation during *in vitro* maturation (Same oocyte used in the top panels
471 of Fig. 5B). DIC images were captured every 10 minutes at Z-intervals of 5 µm. The scale bar
472 represents 50 µm.
473
474 **Supplementary Movie 3:** Time-lapse microscopy of peripheral germinal vesicle (GV) oocyte
475 showing migratory GV relocation during *in vitro* maturation (Same oocyte used in the middle
476 panels of Fig. 5B). DIC images were captured every 10 minutes at Z-intervals of 5 µm. The scale
477 bar represents 50 µm.
478

479 **Supplementary Movie 4:** Time-lapse microscopy of peripheral germinal vesicle (GV) oocyte

480 that failed to relocate its GV during *in vitro* maturation (Same oocyte used in the lower panels of

481 Fig. 5B). DIC images were captured every 10 minutes at Z-intervals of 5 µm. The scale bar

482 represents 50 µm.

483

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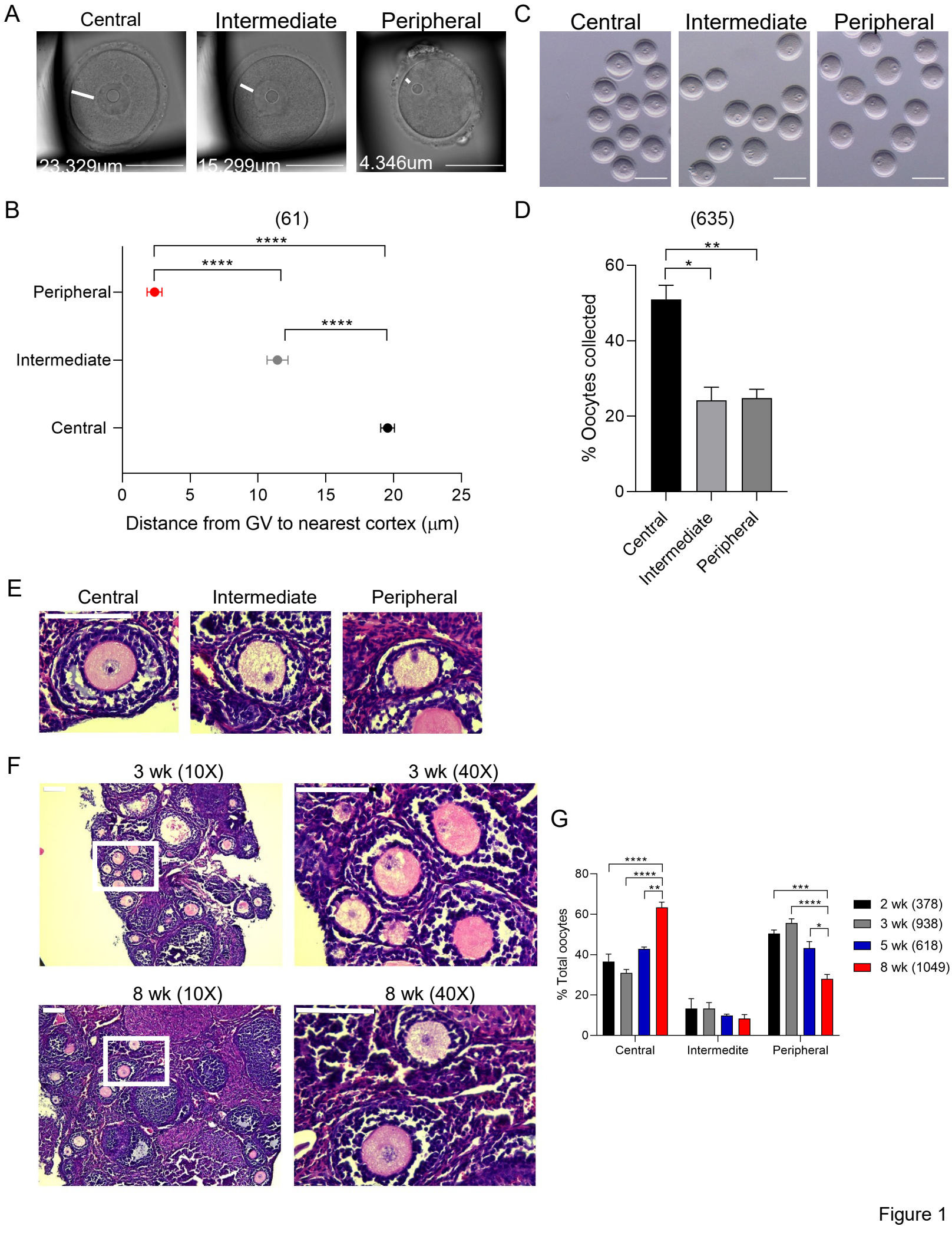

A
Central
Intermediate
Peripheral
23.329um
15.299um
4.346um
C
Central
Intermediate
Peripheral
B
(61)
****
****
****
Peripheral
Intermediate
Central
0
5
10
15
20
25
Distance from GV to nearest cortex (μm)
D
(635)
**
*
60
40
20
0
% Oocytes collected
Central
Intermediate
Peripheral
E
Central
Intermediate
Peripheral
F
3 wk (10X)
3 wk (40X)
8 wk (10X)
8 wk (40X)
G
****
****
**
***
****
*
80
60
40
20
0
% Total oocytes
Central
Intermedite
Peripheral
2 wk (378)
3 wk (938)
5 wk (618)
8 wk (1049)

Figure 1

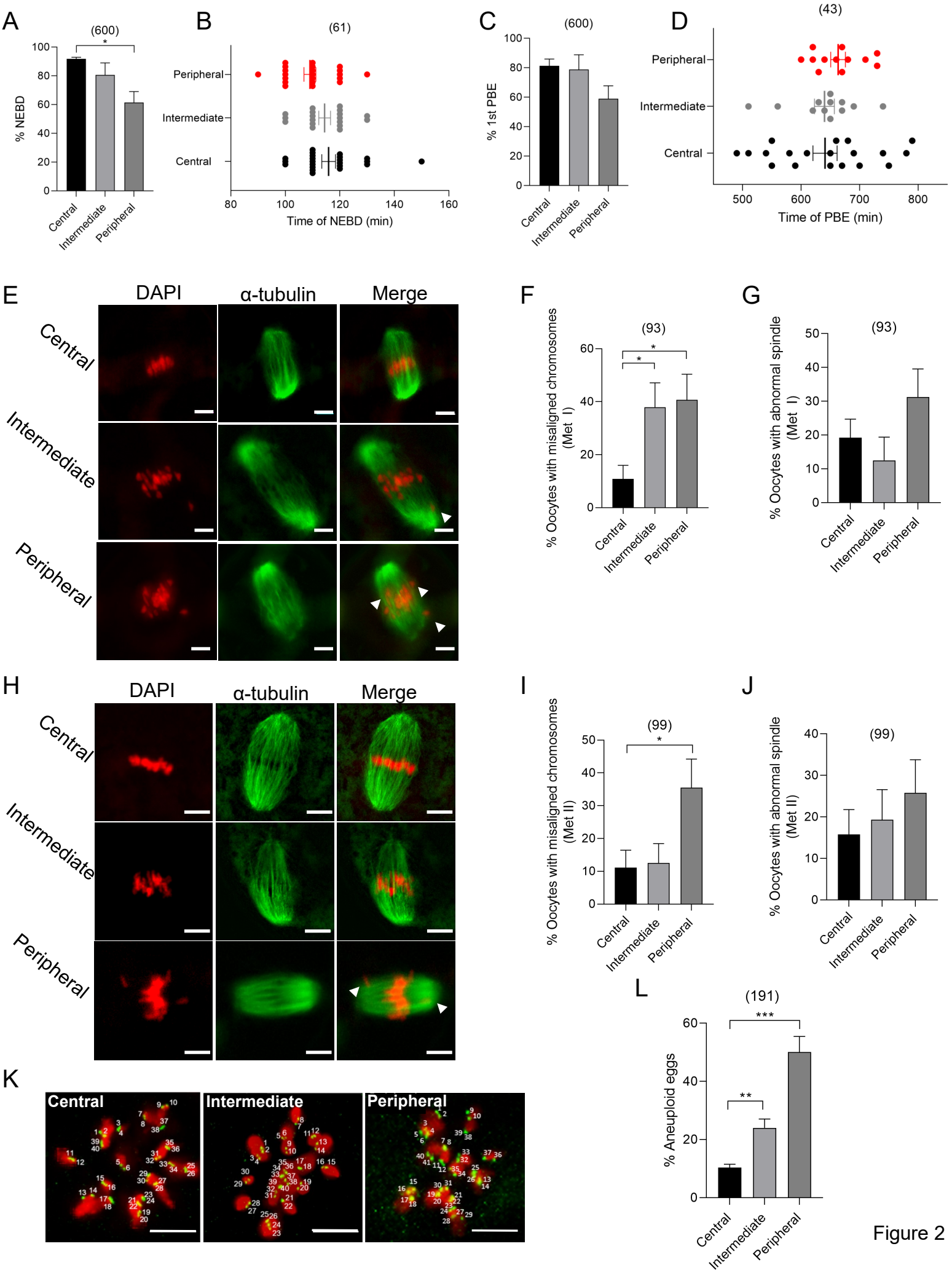

A
(600)
% NEBD
Central
Intermediate
Peripheral
B
(61)
Peripheral
Intermediate
Central
Time of NEBD (min)
C
(600)
% 1st PBE
Central
Intermediate
Peripheral
D
(43)
Peripheral
Intermediate
Central
Time of PBE (min)
E
DAPI
α-tubulin
Merge
Central
Intermediate
Peripheral
F
(93)
% Oocytes with misaligned chromosomes (Met I)
Central
Intermediate
Peripheral
G
(93)
% Oocytes with abnormal spindle (Met I)
Central
Intermediate
Peripheral
H
DAPI
α-tubulin
Merge
Central
Intermediate
Peripheral
I
(99)
% Oocytes with misaligned chromosomes (Met II)
Central
Intermediate
Peripheral
J
(99)
% Oocytes with abnormal spindle (Met II)
Central
Intermediate
Peripheral
K
Central
Intermediate
Peripheral
L
(191)
% Aneuploid eggs
Central
Intermediate
Peripheral

Figure 2

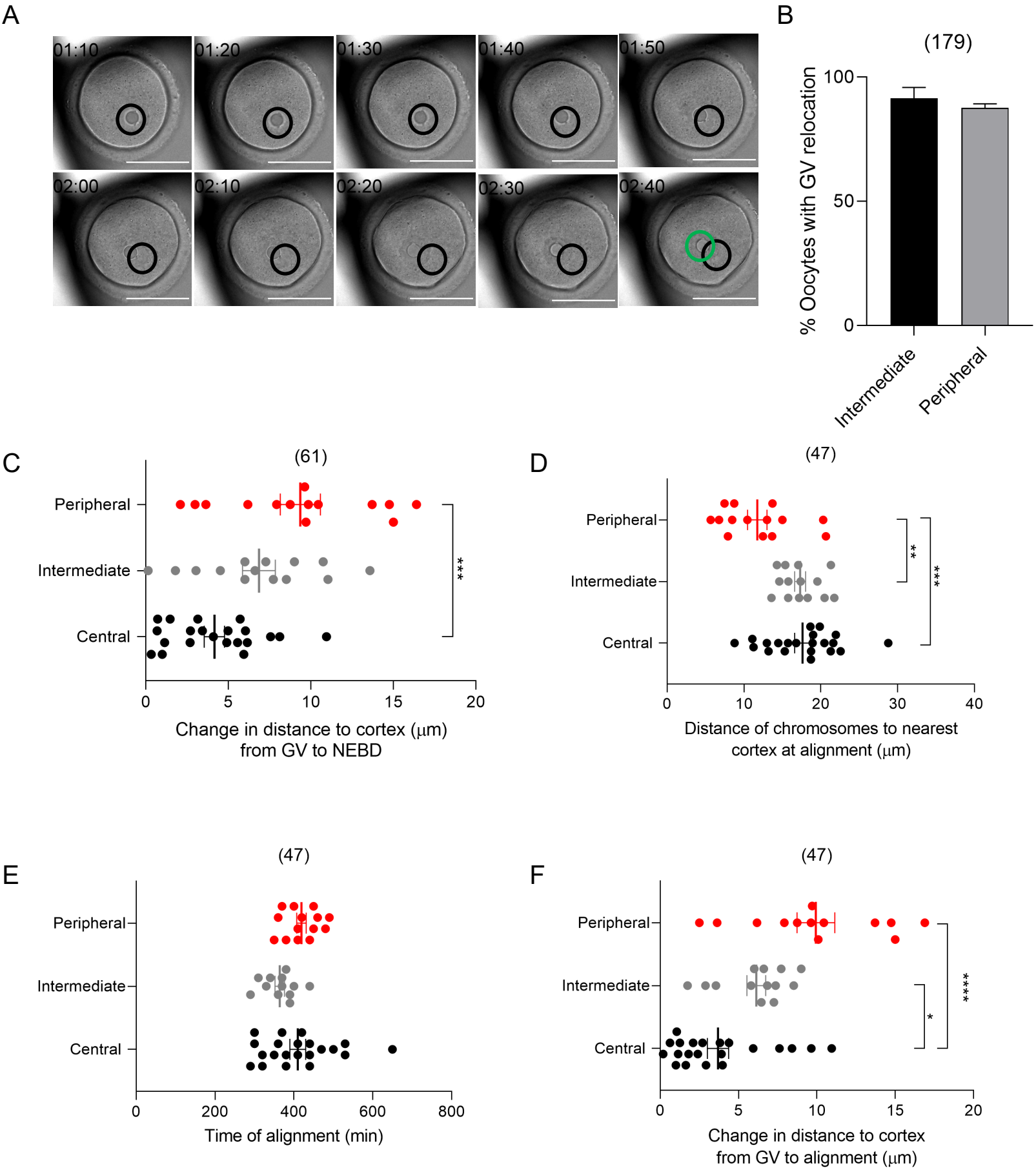

A
01:10
01:20
01:30
01:40
01:50
02:00
02:10
02:20
02:30
02:40
B
(179)
% Oocytes with GV relocation
100
50
0
Intermediate
Peripheral
C
(61)
Peripheral
Intermediate
Central
***
0
5
10
15
20
Change in distance to cortex (μm)
from GV to NEBD
D
(47)
Peripheral
Intermediate
Central
**
***
0
10
20
30
40
Distance of chromosomes to nearest
cortex at alignment (μm)
E
(47)
Peripheral
Intermediate
Central
0
200
400
600
800
Time of alignment (min)
F
(47)
Peripheral
Intermediate
Central
*
****
0
5
10
15
20
Change in distance to cortex
from GV to alignment (μm)

Figure 3

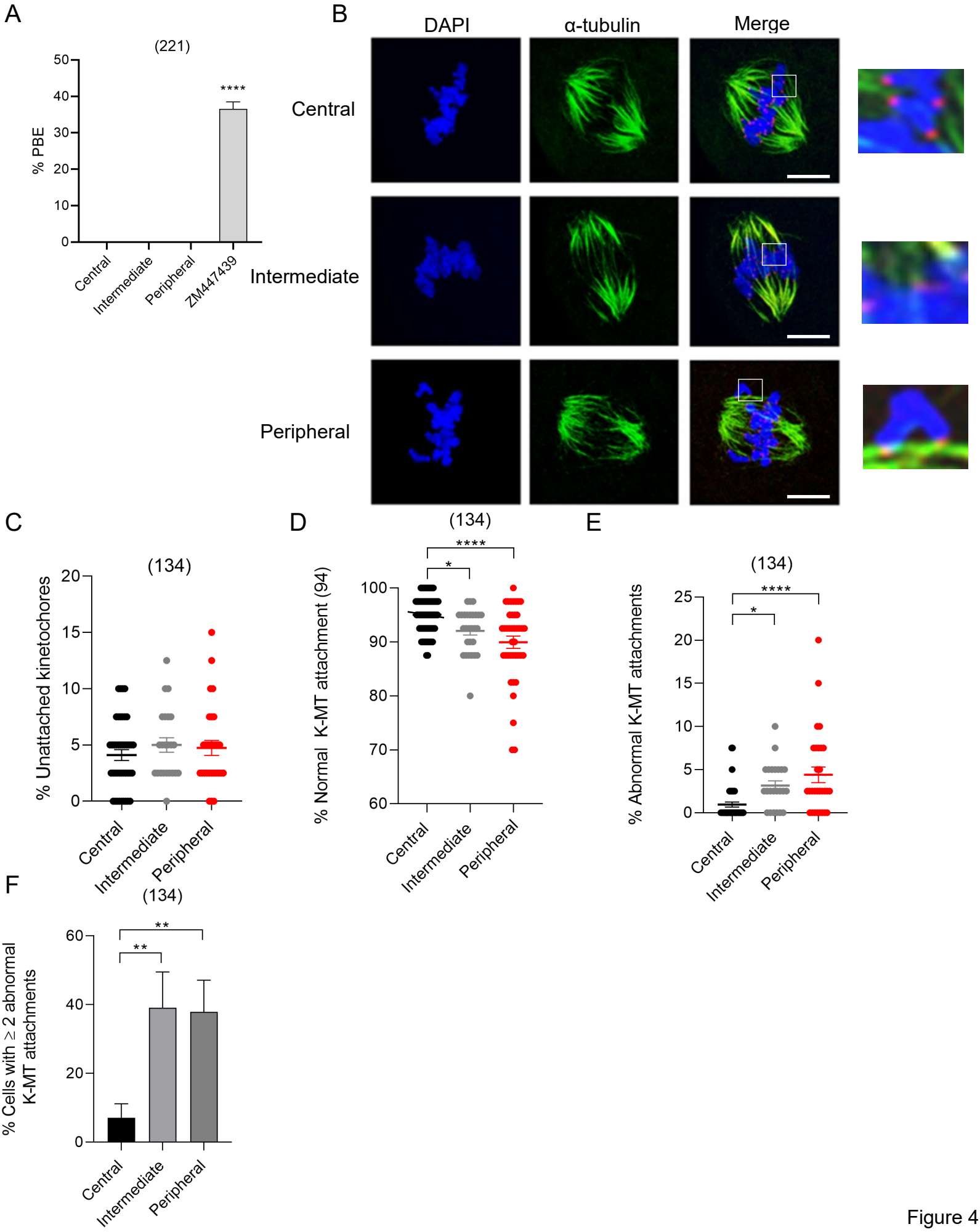
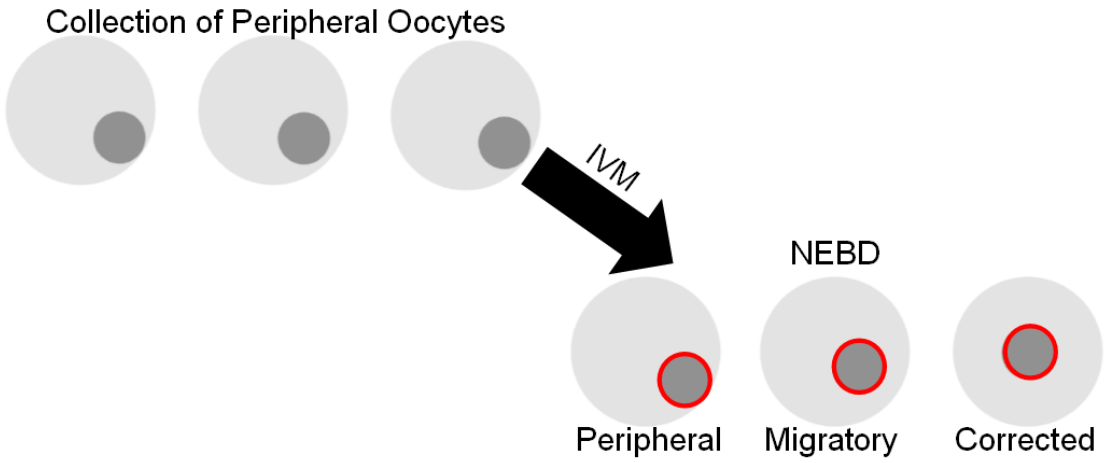
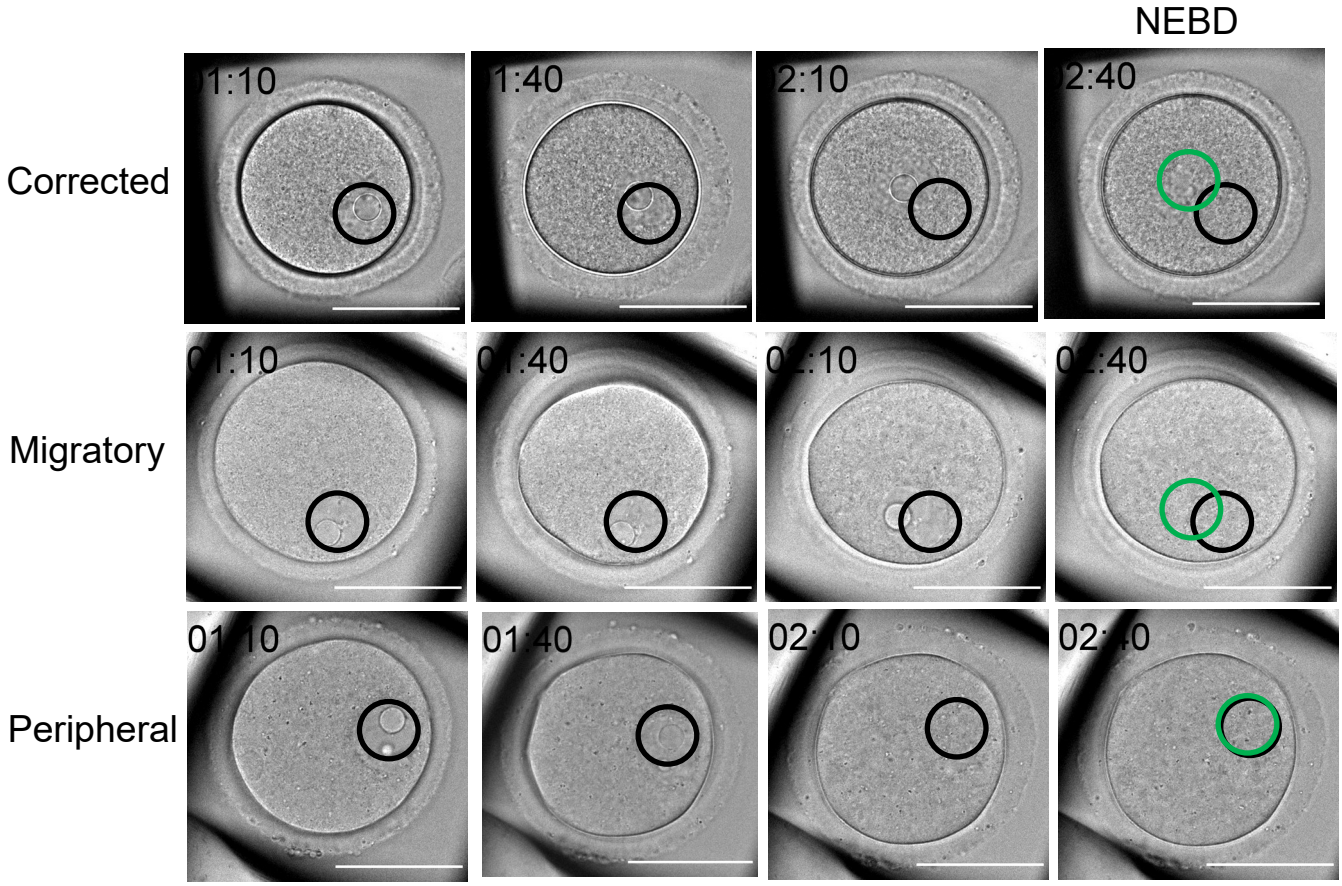

A
(221)
% PBE
50
40
30
20
10
0
****
Central
Intermediate
Peripheral
ZM447439
B
DAPI
α-tubulin
Merge
Central
Intermediate
Peripheral
C
(134)
% Unattached kinetochores
20
15
10
5
0
Central
Intermediate
Peripheral
D
(134)
% Normal K-MT attachment (94)
****
*
100
90
80
70
60
Central
Intermediate
Peripheral
E
(134)
% Abnormal K-MT attachments
****
*
25
20
15
10
5
0
Central
Intermediate
Peripheral
F
(134)
% Cells with ≥ 2 abnormal K-MT attachments
**
**
60
40
20
0
Central
Intermediate
Peripheral

Figure 4

A


Collection of Peripheral Oocytes
IVM
NEBD
Peripheral
Migratory
Corrected

B


NEBD
Corrected
Migratory
Peripheral
01:10
01:40
02:10
02:40

C

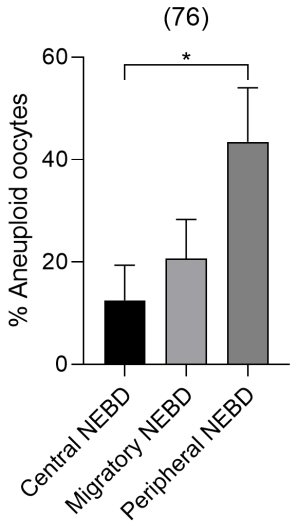

(76)
*
60
40
20
0
% Aneuploid oocytes
Central NEBD
Migratory NEBD
Peripheral NEBD

Figure 5