The PGE_2/Ptger4b pathway regulates ovulation by inducing intracellular actin cytoskeleton rearrangement via the Rho/Rock pathway in the granulosa cells of periovulatory follicles in the teleost medaka

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Abstract

We have previously shown that the prostaglandin E_2/Ptger4b receptor system is involved in ovulation in teleost medaka and induces intracellular actin cytoskeleton rearrangement in the granulosa cells of preovulatory follicles. In this study, we investigated the signaling pathways through which prostaglandin E_2 induces a change in the actin cytoskeleton. Treating preovulatory follicles with GW627368X (Ptger4b antagonist), a Rho inhibitor, or Y-27632 [Rho-associated protein kinase (Rock) inhibitor] inhibited not only in vitro follicle ovulation but also intracellular actin cytoskeleton rearrangement. Active Rhoa-c and Rock1 were detected in follicles immediately before ovulation. GW627368X also inhibited Rhoa-c activation and cytoskeleton rearrangement. PGE_2-induced actin cytoskeleton rearrangement was not observed in the Ptger4b-, Rhoa-c-, or Rock1-deficient OLHNI-2 cells. These results indicate that the PGE_2/Ptger4b pathway regulates intracellular actin cytoskeleton rearrangement via the Rho/Rock pathway in the granulosa cells of preovulatory follicles during medaka ovulation.

42 **1. Introduction**

43 Ovulation is a dynamic process of extrusion of mature oocytes from the interior of the
44 ovary into the ovarian or peritoneal cavity, depending on the species (Espey and Richards,
45 2006; Lubzens et al., 2010), and is induced by the ovulatory surge of gonadotropin
46 luteinizing hormone (LH). This process is closely coordinated by several intracellular and
47 extracellular factors, proteins, and low-molecular-weight substances, including steroid
48 hormones and prostaglandins (PGs). Previous studies have established that many
49 genes/proteins are regulated and induced in the preovulatory follicles in response to LH
50 stimulation, particularly in granulosa cells (GCs). These ovulation-associated
51 genes/proteins have been studied intensively and the information from such studies aids
52 in understanding the nature of LH-induced ovulation in vertebrates (Christenson et al.,
53 2013; Espey and Richards, 2002; Espey and Richards, 2006; Gilbert et al., 2011; Lussier
54 et al., 2017; Richards, 2007; Richards et al., 2015).

55 It is generally accepted that proteolytic degradation of the follicle wall extracellular
56 matrix (ECM) components in the apical region of ovulating follicles is indispensable for
57 successful vertebrate ovulation. However, the proteolytic enzymes responsible for follicle
58 rupture have not yet been identified. In contrast, the mechanism underlying follicle wall
59 degradation has been intensively studied in the teleost medaka. Sequential actions of two

60 distinct proteolytic enzyme systems, the urokinase-type plasminogen activator/plasmin
61 system (Ogiwara et al., 2015) and the matrix metalloproteinase (MMP) system (Ogiwara
62 et al., 2005), are required for the hydrolysis of ECM proteins present in the layers of
63 ovulating follicles. Activation/regulation by intrinsic inhibitors and the roles of individual
64 proteolytic enzymes involved in follicle rupture have been established (Takahashi et al.,
65 2019). More recently, the signaling pathway of the LH-induced expression of MMP-15
66 (also known as MT2-MMP), one of the three MMPs required for follicle rupture during
67 ovulation, has been elucidated (Ogiwara et al., 2021).

68 PGs are a group of biologically active lipid compounds that participate in various
69 physiological processes in vertebrates. PGs have been implicated as important inducers
70 of ovulation in many vertebrate species (Kim and Duffy, 2016; Richards, 1997; Sena and
71 Liu, 2008; Shimada et al., 1986; Sorensen and Goetz, 1993; Takahashi et al., 2013). Mice
72 deficient in cyclooxygenase-2, the rate-limiting enzyme in PG synthesis, exhibit an
73 anovulatory phenotype (Davis et al., 1999). In addition, ovulation rate is reduced in mice
74 lacking the PGE_2 receptor subtype EP2 (Hizaki et al., 1999, Kennedy et al., 1999, Tilley
75 et al., 1999). These findings, together with those of ablate-and-replace experiments in
76 nonhuman primates (Duffy et al., 2019), have established the role of PGE_2 and its receptor,
77 EP2, in the ovulatory process in mammals. An interesting finding from experiments using

78 EP2-knockout mice is that the cumulus-oocyte complex (COC) is abortive in multiple
79 ovulated complexes, indicating that the PGE_2/EP2 receptor system activated after LH
80 stimulation also plays a role in COC expansion in periovulatory follicles (Hizaki et al.,
81 1999). However, the mechanisms underlying PGE_2-induced ovulation are not yet fully
82 understood. Accumulating evidence indicate a critical role of PGs in teleost ovulation.
83 $PGF_{2\alpha}$ and/or PGE_2 play important roles in the ovulatory processes in fish (Takahashi et
84 al., 2018). In vitro ovulation has been shown to be inhibited by indomethacin using yellow
85 perch (Bradley et al., 1994), Japanese eel (Kagawa et al., 2003), zebrafish (Lister et al.,
86 2008) and medaka (Fujimori et al., 2011). In medaka, in which PGE_2 regulates ovulation
87 (Fujimori et al., 2011; Fujimori et al., 2012), the PGE_2 receptor subtype Ptger4b is
88 drastically induced in an LH-dependent manner in large-sized follicles as ovulation
89 approaches. Similar to medaka, studies have demonstrated that Pgr and Ptger4b have
90 pivotal roles in zebrafish ovulation (Baker et al 2019; Baker and Van Der Kraak, 2021;
91 Tang et al., 2016), favoring the possibility of a functional role of PGE_2 in ovulation across
92 teleost species. Despite evidences supporting the contribution of PGE_2 to teleost ovulation,
93 the mechanism by which PGE_2 promotes ovulation remains largely unknown. However,
94 in this context, we previously reported that Ptger4b receptor activation by PGE_2 in the
95 GCs of ovulating follicles of medaka progressively leads to actin depolymerization within

96 the cells as the time of ovulation approaches (Ogiwara and Takahashi, 2016), suggesting
97 a role for the PGE_2/Ptger4b system in actin cytoskeleton remodeling in the GCs of
98 follicles at follicle rupture during ovulation.

99 Dynamic remodeling of the actin cytoskeleton involves the physiological processes,
100 such as cell migration, invasion, and metastasis (Yamaguchi and Condeelis, 2007). The
101 remodeling is regulated by actin polymerization and depolymerization. Rho GTPases,
102 such as Rac, Rho, and Cdc42, are the main regulators of remodeling and play pivotal roles
103 in controlling actin cytoskeleton dynamics (Ridley, 2001). Regulators, such as cofilin,
104 cortactin, LASP-1, Mena, AFAP-110, and profilin are also reported to be involved in
105 controlling the actin cytoskeleton (Najm and El-Sibai, 2014; Yamaguchi and Condeelis,
106 2007). Some studies suggest that the reorganization of the actin cytoskeleton is regulated
107 via the PGE_2/EP pathway in many cellular systems. Adhesion dynamics in dendritic cells
108 are mediated via the PGE_2/EP pathway (van Helden et al., 2008). It is suggested that
109 PGE_2/EP4 signaling mediates actin filament depolymerization in podocytes, resulting in
110 the suppression of filtration barrier function in the cells (Martineau et al., 2004). PGE_2/EP
111 signaling has been demonstrated to modulate the migration of dendritic cells by
112 reorganizing the F-actin cytoskeleton (Diao et al., 2021). The above studies have also
113 shown that cAMP acts as a signaling molecule downstream of the PGE_2 receptor.

114 To extend our hypothesis that the activated PGE_2/Ptger4b system in medaka follicles
115 around the time of follicle rupture induces intracellular actin cytoskeleton rearrangement
116 in follicle cells (Ogiwara and Takahashi, 2016; Takahashi et al., 2018), we examined the
117 signaling pathway involved in the PGE_2/Ptger4b system that leads to cytoskeleton
118 rearrangement during ovulation in medaka. Herein, we report a possible role for the
119 Rho/Rho-associated protein kinase (Rock) pathway in actin rearrangement in the GCs of
120 periovulatory follicles. Our results strengthen the notion that PGE_2 plays a pivotal role in
121 intracellular actin filament rearrangement in the GCs of periovulatory follicles during
122 ovulation in the fish.
123

124 **2. Materials and methods**

125 **2.1. Medaka culture and tissue preparation**

126 Orange-colored medaka fish (*Oryzias latipes*) variants purchased from commercial
127 vendors were used in this study. The fish were kept in a 60-liter tank for at least 14 days
128 to acclimate to 26 °C under a 14/10 h light/dark cycle (Ogiwara et al., 2005). Under these
129 conditions, they spawn daily and ovulate immediately before the light period begins. In
130 this study, the timing, called ovulation time, was set at ovulation hour 0. Preovulatory
131 follicles destined to ovulate (≥1.0 mm, post-vitellogenic phase, stage IX-X) were isolated

132 (Ogiwara et al., 2013). The follicle layers were separated as previously described
133 (Ogiwara et al., 2005). The experimental procedures used in this study were approved by
134 the Committee of the Experimental Plants and Animals, Hokkaido University.
135

136 **2.2. In vitro follicle culture and ovulation**

137 In vitro follicle culture was performed as described previously (Ogiwara and Takahashi,
138 2019). Preovulatory follicles already exposed to the endogenous LH surge were isolated
139 from the ovary 3 h before ovulation and cultured at 26 °C in 90% M199 medium (pH 7.4)
140 with or without 10 μM GW627368X, 0.1-2.5 μg/mL Rho inhibitor (Cytoskeleton, Inc.;
141 Denver, CO), 10 μM ML 141 (Tocris Bioscience; Ellisville, MO), 50 μM Rac1 inhibitor
142 (Wako, Osaka, Japan), 1 μg/mL Rho activator (Cytoskeleton, Inc.), and 0.1-10 μM Y-
143 27632 (Rock inhibitor, Wako). After culturing for 3, 4, 6, or 8 h, the follicles were
144 collected and used for subsequent experiments. The ovulation rate was determined by
145 counting the number of oocytes that successfully ovulated 8 h after incubation.
146

147 **2.3. Cloning**

148 As the nucleotide sequence of medaka *rock1* was different from that currently available
149 from the National Center of Biotechnology Information (NCBI) database

150 (https://www.ncbi.nlm.nih.gov/), the gene was subjected to cDNA cloning. The
151 nucleotide sequence of the *rock1* coding region was determined from follicle cDNA using
152 reverse transcription-polymerase chain reaction (RT-PCR) with KOD Fx DNA
153 polymerase (Toyobo; Osaka, Japan). The primers used were Rock1 pET SS and Rock1
154 cds-AS (Supplementary Table S1). The PCR products were phosphorylated, gel-purified,
155 and ligated into pBluescript SK vector (Agilent Technologies; Santa Clara, CA). The
156 nucleotide sequence of the resulting vector was confirmed by sequencing. The determined
157 sequence was deposited in the DDBJ/GenBank/NCBI database (Accession number:
158 LC726226).
159

160 **2.4. Reverse-transcription and real-time PCR**

161 Total RNA isolation, and real-time quantitative RT-PCR (qRT-PCR) were performed as
162 previously described (Ogiwara and Takahashi, 2016). The primer pairs used are listed in
163 Table S1. To determine the expression level, KOD SYBR qPCR Mix (Toyobo) or KAPA
164 Fast qPCR Kit (Nippon Genetics Co., Ltd.; Tokyo, Japan) was used. To normalize the
165 transcript levels of the target genes, we tested the housekeeping genes, such as
166 cytoplasmic actin (*actb*), 18S rRNA (*rn18s1*), ribosomal protein L7 (*rpl7*), and elongation
167 factor 1a (*eef1a*). The most stably expressed gene in the examined tissues was *eef1a*;

168 therefore, *eef1a* mRNA expression was used for normalization. The qPCR threshold cycle
169 (Ct) value was automatically determined using the instrument' software (Thermal Cycler
170 Dice, Real-Time System II software Ver.5.1.1, TAKARA BIO Inc., Shiga, Japan). The Δ
171 Ct value (Ct value of the reference sample minus Ct of the sample minus) was calculated,
172 and $2^{\Delta Ct}$ was calculated. The relative expression data were generated using the resulting
173 values.
174
175 **2.5. Antibody preparation**
176 Recombinant antigens were produced using *E. coli.* expression system. The coding
177 regions of Rhoa-a and Rhoa-c, or the partial coding region of Rock1 were amplified using
178 PCR with KOD Fx Neo DNA polymerase (Toyobo), and the primer pairs are listed in
179 Table S1. The PCR products were ligated into the pET 30a vector (Novagen; Madison,
180 WI), and the nucleotide sequences were confirmed by sequencing. The recombinant
181 proteins were expressed and purified as previously described (Ogiwara and Takahashi,
182 2007). The purify of the purified proteins was confirmed using SDS-PAGE. After
183 electrophoresis, the gel was stained with 0.25% Coomassie Brilliant Blue (CBB) in 30%
184 methanol, 10% acetic acid, and 40% H_2O. After staining for 20 min, the gel was destained
185 with 30% methanol, 10% acetic acid, and 40% H_2O. Specific antibodies were produced

186 in mice (Ogiwara et al., 2013) and purified (Ogiwara et al., 2012), according to previously
187 described methods. Mouse anti-medaka Rpl7 antibody was prepared as previously
188 described (Ogiwara and Takahashi, 2019).
189

190 **2.6. Tissue extract preparation, immunoprecipitation (IP), and western blot analysis**

191 Follicle extract for IP was prepared from 30 ovarian follicles per sample as previously
192 described (Ogiwara et al., 2021). The follicle layer extract was prepared as previously
193 described (Ogiwara et al., 2005). The protein concentration was determined using a BCA
194 kit (Thermo Fischer Scientific, San Jose, CA). IP and western blotting were performed as
195 previously described (Ogiwara et al., 2021), except that anti-medaka Rhoa-c or anti-
196 medaka Rock1 antibodies were used. We examined the protein expression of Actb,
197 Glyceraldehyde-3-phosphate dehydrogenase, and Rpl7 to select an appropriate protein as
198 a reference using the follicle layer and preovulatory follicle extract. The most stably
199 expressed protein in the examined tissues was Rpl7; therefore, Rpl7 was used as the
200 reference.
201

202 **2.7. Primary granulosa cell (pGC) preparation**

203 GCs were isolated from -1 h follicles, and pGCs were prepared according to a previously

204 described method (Ogiwara and Takahashi, 2016).

205

206 **2.8. Immunohistochemistry**

207 Paraffin sections (5 μm thick) were prepared as previously described (Ogiwara et al.,
208 2015). The sections were dewaxed twice in xylene for 10 min and then placed in 99%
209 ethanol for 2 min. The samples were hydrated using a graded ethanol series and then
210 rinsed with pure water for 5 min. The specimens were then placed in phosphate-buffered
211 saline (PBS) for 2 min and incubated in PBS containing 3% H_2O_2 for 10 min. The sections
212 were then incubated in PBS containing 1% bovine serum albumin (Wako) at room
213 temperature for 60 min and with anti-medaka Rhoa-c or Rock1 antibody diluted in PBS
214 at room temperature for 60 min. They were then washed three times with PBS for 20 min
215 and incubated with a DAKO envision mouse (Agilent Technologies Inc.) for 60 min. After
216 washing three times with PBS for 20 min, the signal was detected using the ImmPACT™
217 AEC HRP Substrate kit (Vector Laboratories, Burlingame, CA). As a negative control,
218 the primary antibody and its antigen (20 μg) were diluted in PBS, preincubated for 16 h
219 at 4°C, and used for immunohistochemistry.

220

221 **2.9. Active Rhoa-c detection**

222 Active medaka Rhoa-c was detected using a RhoA Pull-Down Activation Assay Biochem
223 Kit (Cytoskeleton Inc.) according to the manufacturer's instructions. For sample
224 preparation, follicle layers from preovulatory follicles or follicles cultured with chemicals
225 were homogenized in the cell lysis buffer supplied in the kit. The sample was then
226 centrifuged at 12,000 ×g for 10 min, and the resulting supernatant was used for the assay.
227 Active Rhoa-c was detected by western blot analysis using an anti-medaka Rhoa-c
228 antibody.
229

230 **2.10. *rhoa-c*, *rock1*, or *ptger4b* knockout in OLHNI-2 cells**

231 The knockout was performed using CRISPR/Cas9-mediated genome editing according to
232 a previous method (Ogiwara et al., 2021). Briefly, the oligonucleotide pair listed in Table
233 S1 was annealed and ligated to pDR274, and a medaka caudal fin cell line (OLHNI-2)
234 derived from the HNI strain, which was obtained from the RIKEN BioResource Center
235 (Tsukuba, Japan), was co-transfected with the vector and Cas9 nuclease expression vector
236 carrying a hygromycin B resistance gene. After hygromycin B selection, the cells were
237 used for the experiments.
238

239 **2.11. G-/F-actin detection**

The G-/F-actin ratio was measured as previously described (Ogiwara and Takahashi, 2016). Briefly, OLHNI-2 cells and follicle layers from preovulatory follicles or follicles cultured with chemicals were gently homogenized in an actin stabilization buffer to prepare the G-actin and F-actin fractions. The samples were then subjected to western blot analysis. The actin bands were detected using an anti-medaka Actb antibody.

2.12. Statistical analysis

To validate our results, all experiments were repeated 3-8 times. The data collected were subjected to statistical analysis using Excel software, and the mean of 3-8 replicates was evaluated as the mean ± standard error of the mean. Significance was determined using Student’s t-test or one-way analysis of variance (ANOVA) followed by Dunnett's or Tukey's post hoc test, as appropriate, and presented as $P<0.05$ (*) or $P<0.01$ (**). Equal variation was confirmed using the F-test or Bartlett’s test as appropriate. For western blotting and immunohistochemical analyses, at least three separate experiments were performed to confirm the reproducibility of the findings, and the representative results of all experiments are shown.

3. Results

258 **3.1. Rho inhibitor inhibits in vitro ovulation in medaka**

259 Our previous study reported that Ptger4b activation did not activate or inhibit adenylate
260 cyclase in the OLHNI2 cell line; thus, Ptger4b is strongly suggested to be coupled with
261 G12/13 or Gq/G11 to activate the Ptger4b signaling pathway (Takahashi et al., 2018).
262 This possibility was examined using in vitro follicle culture. It is well established that
263 G12/13 proteins can couple with G-protein-coupled receptors to activate RHO by
264 regulating the activity of RhoGTPase nucleotide exchange factors (Siehler, 2009; Vogt,
265 2003). We first examined whether RHO family protein(s), including RHO, CDC42, and
266 RAC1 (Tapon and Hall, 1997), are involved in medaka ovulation. When -3 h follicles
267 were cultured with or without each RHO family member inhibitor, in vitro ovulation was
268 significantly inhibited by the RHO inhibitor (Fig. 1A). No significant inhibitory effects
269 were observed in follicles treated with the CDC42 inhibitor ML141 or the RAC1 inhibitor.
270 Ovulation was blocked in a dose-dependent manner by an RHO inhibitor (Fig. 1B).
271 Incubating -3h follicles with GW627368X, an EP4 antagonist, strongly inhibited in vitro
272 ovulation, which was ameliorated by adding the RHO activator (Fig. 1C). These results
273 indicate that Rho acts in the Ptger4b signaling pathway and Rho activation is required for
274 successful medaka ovulation.

275

276 **3.2. Rho mRNA and protein expression in preovulatory follicles during a 24 h**
277 **spawning cycle**

278 As Rho is an important factor in the Ptger4b signaling pathway and medaka
279 ovulation, a medaka genome database was searched using the Ensembl genome browser
280 (Ensembl database, https://www.ensembl.org/index.html) to identify the *rho* gene(s)
281 responsible for the Ptger4b signaling pathway. Six *rho* genes, *rhoa-a, rhoa-b*, *rhoa-c*,

282 *rhob*, *rhog*, and *rhou*, were identified. Real-time RT-PCR analysis of mRNAs of these
283 genes revealed that all the RNAs were present, with the highest expression for *rhoa-c* and
284 the second highest for *rhoa-a* in the follicle layers of the -3 h follicles (Fig. 2A). *rhoa-a*
285 and *rhoa-c* mRNA expression patterns in the preovulatory follicle during a 24 h spawning
286 cycle were examined. Both mRNAs were constitutively expressed in the follicles (Fig.
287 2B and C).

288 To detect Rho proteins in preovulatory follicles, we generated a mouse polyclonal
289 antibody raised against medaka Rhoa-a and Rhoa-c. Recombinant medaka Rhoa-a and
290 Rhoa-c were produced in an *E. coli* expression system and used separately as antigens for
291 immunization. The antibody cross-reacted with the respective antigens. However, the
292 antigen was not recognized by the absorbed antibody, indicating that the antibodies were
293 specific (Fig. 2D). The anti-Rhoa-c antibody detected the protein in the preovulatory
294 follicles; however, no bands were detected with the anti-Rhoa-a antibody (data not
295 shown). We further examined the expression of Rhoa-c in preovulatory follicles during a
296 24 h spawning cycle. The corresponding proteins associated with the preovulatory
297 follicles were detected by IP and western blotting using an antibody. The antibody
298 constitutively detected Rhoa-c, irrespective of when the extracts were prepared from
299 intact preovulatory follicles in the 24-h spawning cycle (Fig. 2E). Western blot analysis
300 revealed that Rhoa-c was expressed in GCs (Fig. 2F).

301 Immunohistochemical experiments using fish ovary sections collected 3 h before
302 ovulation were conducted to determine Rhoa-c localization, which showed the highest
303 mRNA expression in the -3 h-follicles in PCR analysis. Rhoa-c was localized in the
304 follicle layer of the largest or post-vitellogenic follicles (stage X; Fig. 2G, arrows and
305 asterisks) and was also expressed in the follicle layer of follicles larger than 150 μm,

306 which were in an early-, late-, or post-vitellogenic phase at stages V–IX (Fig. 2 G,
307 arrowheads). No signal was observed in the section stained with a pre-adsorbed
308 antibody/antigen complex, which was the antibody preincubated with its antigen
309 (absorbed antibody), indicating that the signal was specific (Fig. 2 G, lower panel). These
310 results indicate that Rhoa-c is expressed in the follicle layers of both vitellogenic and
311 post-vitellogenic follicles. These results also indicate that the Rho protein plays a role in
312 PGE_2/Ptger4b signaling in follicle layers.

313

314 **3.3. Active Rhoa-c detection in follicles about to ovulate**

315 To examine whether the PGE_2 pathway mediates Rho activation in medaka
316 preovulatory follicles, a pull-down assay was conducted to detect active Rho in the
317 follicles. Active Rhoa-c was pulled-down from the extracts and the precipitating Rhoa-c
318 was detected by western blot analysis. Active Rhoa-c was detected in the -3 and -1 h
319 follicles but not in the -6 h follicles (Fig. 3A). Rhoa-c was activated after incubating the
320 -3 h follicles with PGE_2 in vitro, which was inhibited by GW627368X. However, this
321 inhibitory effect was abolished by the addition of the Rho activator (Fig. 3B). No
322 inhibitory effects were observed when the follicles were cultured with Rho or Rock
323 inhibitors. These results indicate that Rhoa-c is activated downstream of Ptger4b.

324

325 **3.4. Rock involvement in medaka ovulation**

326 Rho exerts its biological effects by binding to its downstream effector molecules
327 including Rock, an important downstream factor. As active Rhoa-c was detected in
328 follicles about to ovulate, we examined whether Rock might be involved in medaka
329 ovulation. In vitro ovulation was significantly suppressed in a dose-dependent manner
330 after culturing preovulatory follicles with the Rock inhibitor, which was not abolished
331 after culturing the follicles with both the Rock inhibitor and Rho activator (Fig. 4A, B).
332 To predict the timing of Rock activation, we examined the in vitro ovulation rates after
333 exposing the follicles to the inhibitor for various time periods (Fig. 4C). Ovulation was
334 strongly inhibited when the follicles were cultured in the presence of Rock inhibitor for
335 8 h (-3 to +5 h), 7 h (-2 to +5 h), and 6 h (-1 to +5 h). Exposure of the follicles to the
336 inhibitor for 1 h (-3 to -2 h) or 2 h (-3 to -1 h) did not inhibit ovulation significantly. The
337 above results suggest that Rock is involved in medaka ovulation, and that kinase activity
338 is required for successful ovulation between -1 h and 0 h.

339

340 **3.5. Rock mRNA and protein expression in the preovulatory follicles during 24 h**
341 **spawning cycles**

342 A datadase search for medaka *rock* genes using the Ensembl genome database
343 revealed that the fish possessed three *rock* genes: *rock1, rock2a*, and *rock2b*. Among these
344 *rock* genes, *rock1* expression levels were highest in the follicle layers of -3 h follicles (Fig.

345 5A). Therefore, *rock1* was further analyzed by studying *rock1* mRNA expression in
346 preovulatory follicles using the total RNA extracted from intact follicles obtained from
347 the ovaries at various time points during the 24-h spawning cycle (Fig. 5B). The *rock1*
348 transcript levels were almost constant in the preovulatory follicles during the spawning
349 cycle.

350 A mouse polyclonal antibody for recombinant medaka Rock1 was prepared and its
351 specificity was confirmed (Fig. 5C). Western blot analysis was performed using follicle
352 layer extracts to detect Rock1 protein. The corresponding protein associated with the
353 follicle layer of the preovulatory follicles was detected using the antibody at position 158
354 kDa in all the extracts examined, corresponding to the size predicted for the medaka
355 Rock1 protein (Fig. 5D). Western blot analysis revealed that the Rock1 protein was
356 expressed in the GCs (Fig. 5E). In the immunohistochemical analysis of the fish ovary
357 sections 3 h before ovulation, the medaka Rock1 antibody detected positive signals
358 associated with the follicle layer of the largest follicle (stage X) (Fig. 5F, arrows and
359 asterisks). Signals were also detected in the follicle layer of follicles larger than 150 μm,
360 corresponding to the early-, late-, or post-vitellogenic phases (stages V–IX) (Fig. 5 F,
361 arrowheads). In stage X follicles, positive signals for Rock1 protein were localized in
362 GCs (Fig. 5 F, lower right panel). No signal was observed in the section stained with a

363 pre-adsorbed antibody/antigen complex, which was the antibody pre-incubated with the

364 antigen (absorbed antibody) (Fig. 5 F, upper right panel).

365

366 **3.6. PGE_2 modulates actin filament polymerization in the follicle cells of follicles**

367 **about to ovulate via the Rho/Rock pathway.**

368 Our previous studies suggested that the PGE_2/Ptger4b signaling cascade is involved

369 in intracellular actin cytoskeleton rearrangement in follicle cells of follicles about to

370 ovulate (Ogiwara and Takahashi, 2016; Takahashi et al., 2018). To examine whether the

371 Rho/Rock pathway is involved in actin filament rearrangement, we analyzed the actin

372 cytoskeleton polymerization status in follicle cells of follicles cultured with reagents that

373 affect the Rho/Rock pathway. The G-/F-actin ratio increased significantly when follicles

374 were cultured without any inhibitor. This increase was inhibited by GW627368X;

375 however, this inhibition was abolished by adding the Rho activator together with the

376 antagonist. The G-/F-actin ratio did not increase in follicles treated with Rho or Rock

377 inhibitor (Fig. 6A).

378 OLHNI-2 cells, which express Ptger4b, Rhoa-c, and Rock, were treated with PGE_2 to

379 examine the effects of these proteins on changes in rearrangement (Fig. 6B). The G-/F-

380 actin ratio significantly increased at 6 h after PGE_2 treatment. Next, we analyzed the ratio

381 of Rhoa-c-, Rock1-, and Ptger4b-deficient OLHNI-2 cells. No bands for Rhoa-c or Rock1

382 were detected in the knockout cells (Fig. 6C). We could not examine Ptger4b protein

383 expression in knockout cells, because a Ptger4b-specific antibody was not available. The

384 G-/F-actin ratio was significantly increased in PGE_2-treated cells, but not in PGE_2-treated

385 knockout cells (Fig. 6D).

386 These results indicate that PGE_2/Ptger4b and its downstream Rho/Rock system are
387 involved in intracellular actin cytoskeleton rearrangement.

388

389 **4. Discussion**

390 We previously reported that the PGE_2/Ptger4b system is involved in medaka
391 ovulation (Fugimori et al., 2011; Fugimori et al., 2012) and that PGE_2 exerts its effects
392 through Ptger4b between -1 and 0 h of ovulation (Fugimori et al., 2012). Moreover, we
393 have previously suggested that PGE_2/Ptger4b-mediated intracellular actin cytoskeleton
394 rearrangement in follicles about to ovulate is important for medaka ovulation (Ogiwara
395 and Takahashi, 2016; Takahashi et al., 2018). This study was conducted to further
396 substantiate the role of the PGE_2/Ptger4b system in follicle ovulation and clarify the
397 signaling cascade of the system. The results of this study strengthen the notion that
398 intracellular actin cytoskeleton rearrangement in the GCs of ovulating follicles is
399 necessary for successful ovulation in medaka. This study also revealed that PGE_2/Ptger4b
400 system activation-induced changes in the cytoskeleton during ovulation are mediated via
401 the Rho/Rock pathway.

402 The rationale for our conclusion that PGE_2/Ptger4b induces intracellular actin
403 cytoskeleton rearrangement via the Rho/Rock pathway in the GCs of preovulatory
404 follicles at ovulation is as follows: (i) Rhoa-c and Rock1 proteins were expressed in the

405 GCs of preovulatory follicles (Fig. 2F and 5E). (ii) Rhoa-c was activated in follicle cells
406 of follicles immediately before ovulation (Fig. 3). (iii) The G-/F-actin ratio increased in
407 the GCs of the follicles immediately before ovulation, and at or around the time of
408 ovulation in the control follicles. In contrast, treatment of preovulatory follicles with a
409 Ptger4b antagonist, Rho inhibitor, or Rock inhibitor suppressed in vitro follicle ovulation
410 and inhibited the increase in the G-/F-actin ratio (Fig. 1, 4, and 6). (iv) Rhoa-c was
411 activated and the G-/F-actin ratio increased during control follicle ovulation; however,
412 opposite results were noted in both events aftert GW627368X treatment. GW627368X-
413 mediated ovulation inhibition was abolished by further treatment with Rho activator (Fig.
414 1, 3, and 6). (v) The G-/F-actin ratio significantly increased in control OLHNI-2 cells
415 following treatment with PGE_2. However, this PGE_2-induced G-/F-actin ratio increase
416 was not detected in Ptger4b-, Rhoa-c-, or Rock1-deficient cells (Fig. 6). Based on these
417 results and our previous findings (Ogiwara and Takahashi, 2016), we proposed a pathway
418 for the induction of actin cytoskeleton rearrangement. PGE_2, secreted by GCs (Ogiwara
419 and Takahashi, 2016; Takahashi et al., 2018), activates Rhoa-c. Currently, the pathway
420 through which active Rock1 causes intracellular actin cytoskeleton rearrangement
421 remains unknown. In mammals, the LIM-Kinase (LIMK)/cofilin pathway (Venessa T
422 Chin et al., 2015), myosin light chain kinase (MLCK) (Sharanek et al., 2016), and ERM

423 (ezrin, radixin, moesin) proteins (Jiao et al., 2017), are reported to be activated by the
424 Rho/Rock pathway to regulate intracellular actin cytoskeleton rearrangement. We
425 examined whether these factors are involved in PGE_2-induced intracellular actin
426 cytoskeleton rearrangement in medaka ovulatory follicles. However, in vitro follicle
427 ovulation was not significantly inhibited when follicles were cultured with LIMK or
428 MLCK inhibitors (data not shown). Ogiwara and Takahashi (2016) reported that moesin
429 A is involved in the regulation of intracellular actin cytoskeleton rearrangement. In the
430 present study, GW627368X did not inhibit moesin A phosphorylation (data not shown),
431 suggesting that moesin A is not a downstream target of Rock1 (Ogiwara and Takahashi,
432 2016). We speculate that there is a novel pathway for inducing actin filament
433 rearrangement that involves factor(s) other than LIMK/Coffin, MLCK, and ERM proteins
434 downstream of Rock1 in medaka ovarian follicles.

435 Pendergrass and Schroeder (1976), Jalabert and Szöllösi (1975), and Trubnikova
436 (2003) reported that cytochalasin B, an actin polymerization inhibitor, inhibits ovulation
437 in medaka, trout, and sturgeons, respectively. Thus, actin cytoskeleton rearrangement
438 accompanying ovulatory processes may be common among teleosts. However, the
439 mechanism underlaying cytochalasin-B-mediated teleost ovulation inhibition remains
440 unclear. However, the results reported by Ogiwara and Takahashi (2016) and those of the

441 present study provide information that answers this long-standing question. An alteration
442 in the extent of actin polymerization within follicle cells, particularly in GCs, is required
443 for LH-induced ovulation; therefore, a disturbance of actin cytoskeleton rearrangement
444 by cytochalasin B treatment most likely causes anovulation. Studies on follicle rupture
445 during ovulation in medaka have established that successful ovulation is assured by the
446 activation of two events induced after the LH surge: ECM protein hydrolysis in the follicle
447 layers of ovulating follicles (Ogiwara et al., 2005; Takahashi et al., 2019) and actin
448 cytoskeleton rearrangement in GCs (Fujimori et al., 2011; Fujimori et al., 2012; Hagiwara
449 et al., 2014; Ogiwara and Takahashi, 2016). The removal of ECM proteins surrounding
450 the GCs by proteolytic enzymes and changes in the intracellular actin cytoskeleton in GCs
451 disintegrates cell-cell interactions in GCs, oocytes, and neighboring GCs. This probably
452 increases GC mobility, facilitating the formation of openings in the apical region through
453 which the oocyte can escape from the periovulatory follicles.

454 In summary, the results of this study revealed that actin cytoskeleton rearrangement
455 is regulated by the PGE_2/Ptger4b system via the Rho/Rock pathway. Although several
456 studies have implicated intracellular actin cytoskeleton in teleost ovulation, its
457 physiological relevance remains unclear. This study is the first to report that Rhoa-
458 c/Rock1 regulates actin cytoskeleton rearrangement during ovulatory processes in

459 medaka. Further studies should focus on identifying additional factors involved in PGE_2-
460 induced actin cytoskeleton rearrangement during ovulation to fully understand the
461 signaling pathways and regulatory mechanisms of this process.
462

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466 Technology of Japan.
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673

674 Figure legends

675 **Fig. 1. Effects of RHO inhibitor, ML141, and RAC inhibitor on in vitro ovulation in**
676 **preovulatory follicles.** (A) The -3 h follicles were cultured for 8 h in the presence of Rho
677 inhibitor (Rho-i), ML 141, or Rac1 inhibitor (Rac1-i), and the ovulation rates were
678 determined. **P<0.01 (ANOVA and Dunnett's post hoc test, N =6). (B) The -3 h follicles
679 were cultured with Rho inhibitor at the indicated concentration. The ovulation rates were
680 determined after incubating for 8 h. *P<0.05, **P<0.01 (ANOVA and Dunnett's post hoc
681 test, N=6). (C) The -3 h follicles were cultured with GW627368X (GW) or both GW and
682 Rho activator (Rho-act). The ovulation rates were determined after incubating for 8 h.
683 **P<0.01 (ANOVA and Dunnett's post hoc test, N=6).

684

685 **Fig. 2. *rho*/Rho expression in medaka ovary.** (A) Real-time RT-PCR analysis was
686 conducted for *rho* genes using total RNA purified from the follicle layers isolated from
687 the preovulatory follicles 3 h before ovulation. (N=3). (B and C) Real-time RT-PCR
688 analysis was conducted for (B) *rhoa-a* and (C) *rhoa-c* using total RNA purified from the
689 preovulatory follicles isolated from ovaries at the indicated time points (N=5-7). (D)
690 Specificity of the antibodies for medaka Rhoa-a (left) and Rhoa-c (right) were examined.
691 Recombinant proteins for antigen were analyzed using CBB staining (CBB) or western
692 blot analysis using purified (WB) or recombinant protein-pretreated (WB(abs))
693 antibodies (left panels in each set). (E) Rhoa-c was detected by
694 immunoprecipitation/western blotting. As a negative control, -3 h follicle extract was
695 immunoprecipitated using normal mouse IgG bound to protein G-sepharose. The arrow
696 indicates Rhoa-c, and the asterisk denotes the band corresponding to the antibody used

697 for immunoprecipitation. As a positive control, Rpl7 was detected using the input
698 fractions. (F) Rhoa-c was detected by western blotting using the extracts prepared from
699 follicular layer (FL) and pGC. Rpl7 was used as a loading control. (G)
700 Immunohistochemical analyses were performed in sections of the -3 h ovary. Purified
701 anti-medaka Rhoa-c antibody (upper and middle panels) or the antibody previously
702 treated with recombinant Rhoa-c (absorbed antibody) was used as a control (lower panel).
703 The area indicated by a box in the upper panel is displayed at higher magnification in the
704 middle panel. The follicle layer (arrows) of large preovulatory follicles (*) and the follicle
705 layer (arrowheads) of medium-size follicles are positively stained. A representative result
706 of four independent experiments is shown. Bars =300 μm in the upper and lower panels
707 and 100 μm in the middle panel.
708
709 **Fig. 3. Detection of active Rhoa-c in the follicle layer of preovulatory follicles and**
710 **the follicles cultured with GW, Rho inhibitor, Rho-associated protein kinase**
711 **inhibitor, and Rho-activator.** (A) Active Rhoa-c was detected in follicle layer extracts
712 prepared at the indicated time points. (B) The -6 h follicles were cultured with no additives
713 for 0 h (-6 h layer), 3 h (Cont (3 h)), or 6 h (Cont (6 h)). The -6 h follicles were cultured
714 with GW, Rho inhibitor (Rho-i), Rho-associated protein kinase (Rock) inhibitor (Rock-i),
715 or both GW and Rho-activator for 6 h and then used to detect active Rhoa-c. Extracts of
716 (A) -1 h or (B) -6 h follicle layers were boiled for 10 min and used as a negative control
717 (Rtn). Active Rhoa-c was pulled-down from the extracts and the precipitating Rhoa-c was
718 detected by western blot analysis. Arrows indicate signals for active Rhoa-c. Total Rhoa-
719 c protein (control) was detected using the input fractions.
720

721 **Fig. 4. Effects of Rho-associated protein kinase (Rock) inhibitor on in vitro ovulation**
722 **in preovulatory follicles.** (A) The -3 h follicles were cultured with Rock inhibitor Y-
723 27632, and the ovulation rates were determined after incubating for 8 h. **P<0.01
724 (ANOVA and Dunnett's post hoc test, N=6). (B) The -3 h follicles were cultured with
725 Rock inhibitor or both the inhibitor and Rho activator (Rho-act). The ovulation rates were
726 determined after incubating for 8 h. **P<0.01 (ANOVA and Dunnett's post hoc test, N=6).
727 (C) The -3 h follicles were cultured with the inhibitor. Black bars and straight lines denote
728 the duration of follicle incubation with or without the inhibitor, respectively (left). The
729 ovulation rates were determined after incubation for 8 h. **P<0.01 (ANOVA and
730 Dunnett's post hoc test, N=6).
731
732 **Fig. 5. *rock1*/Rock1 expression in the medaka ovary.** (A) Real-time RT-PCR analysis
733 was conducted for *rock* genes using total RNA purified from the follicle layers isolated
734 from the follicles 3 h before ovulation. (N=3). (B) Real-time RT-PCR analysis was
735 conducted for *rock1* using total RNA purified from the preovulatory follicles isolated
736 from ovaries at the indicated time points (N=5-7). (C) Specificity of the antibody for
737 medaka Rock1 were examined. Recombinant protein for antigen was analyzed using CBB
738 staining (CBB) or western blot analysis using purified (WB) or recombinant protein-
739 pretreated (WB(abs)) antibodies. (D) Rock1 was detected by western blot analysis using
740 the extract purified from the follicle layer of preovulatory follicles isolated at the indicated
741 time points. Rpl7 was used as a loading control. (E) Rock1 was detected by western
742 blotting using the extracts prepared from follicular layer (FL) and pGC. Rpl7 was used as
743 a loading control. (F) Immunohistochemical analyses were performed in sections of the -
744 3 h ovary. Purified anti-medaka Rock1 antibody (two left and lower right panels) or the

745 antibody previously treated with recombinant Rock1 (absorbed antibody) was used as a
746 control (upper right panel). The area indicated by a box in the upper left panel is displayed
747 at higher magnification in the lower left panel. The area indicated by a box in the lower
748 left panel is displayed at further higher magnification in the lower right panel. The follicle
749 layer (arrows) of large preovulatory follicles (*) and the follicle layer (arrowheads) of
750 medium-size follicles were positively stained. TC, theca cell; GC, granulosa cell; OM,
751 oocyte membrane. A representative result of four independent experiments is shown. Bars
752 =300 μm in the two upper panels and 100 μm in the lower left panel.
753
754 **Fig. 6. The G-/F-actin ratio in the GCs of the preovulatory follicle or OLNI-2 cell.**
755 (A) The -4h follicles were incubated with GW627368X (GW), Rho inhibitor (Rho-i),
756 Rock inhibitor (Rock-i), or with both GW and Rho-activator for 4 h. Follicles cultured
757 without additives (-4 h layer and Cont) were also used as controls. After incubation for 4
758 h, G-actin and F-actin in the follicular layers were detected (lower two panels), and the
759 signal intensities of the bands were densitometrically quantified to determine the G-/F-
760 actin ratio. *P<0.05 (ANOVA and Dunnett's post hoc test, N=4). (B) OLHNI-2 cells were
761 treated with 100 nM PGE_2, and G-/F-actin ratio was determined. *P<0.05 (ANOVA and
762 Dunnett's post hoc test, N=4). (C) Rhoa-c (left) and Rock1 (right) were detected by
763 western blotting using the extracts of OLHNI-2 cell (Cont), or cells without medaka
764 Rhoa-c (Rhoa-c KO) or Rock1 (Rock1 KO). Rpl7 was used as a loading control. (D)
765 OLHNI-2 cells without medaka Rhoa-c (Rhoa-c KO), Rock1 (Rock1 KO), or Ptger4b
766 (Ptger4b KO) were cultured with or without 100 nM PGE_2 and G-/F-actin ratio was
767 determined as in (A). *P<0.05 (t-test, N=3).

Fig. 1

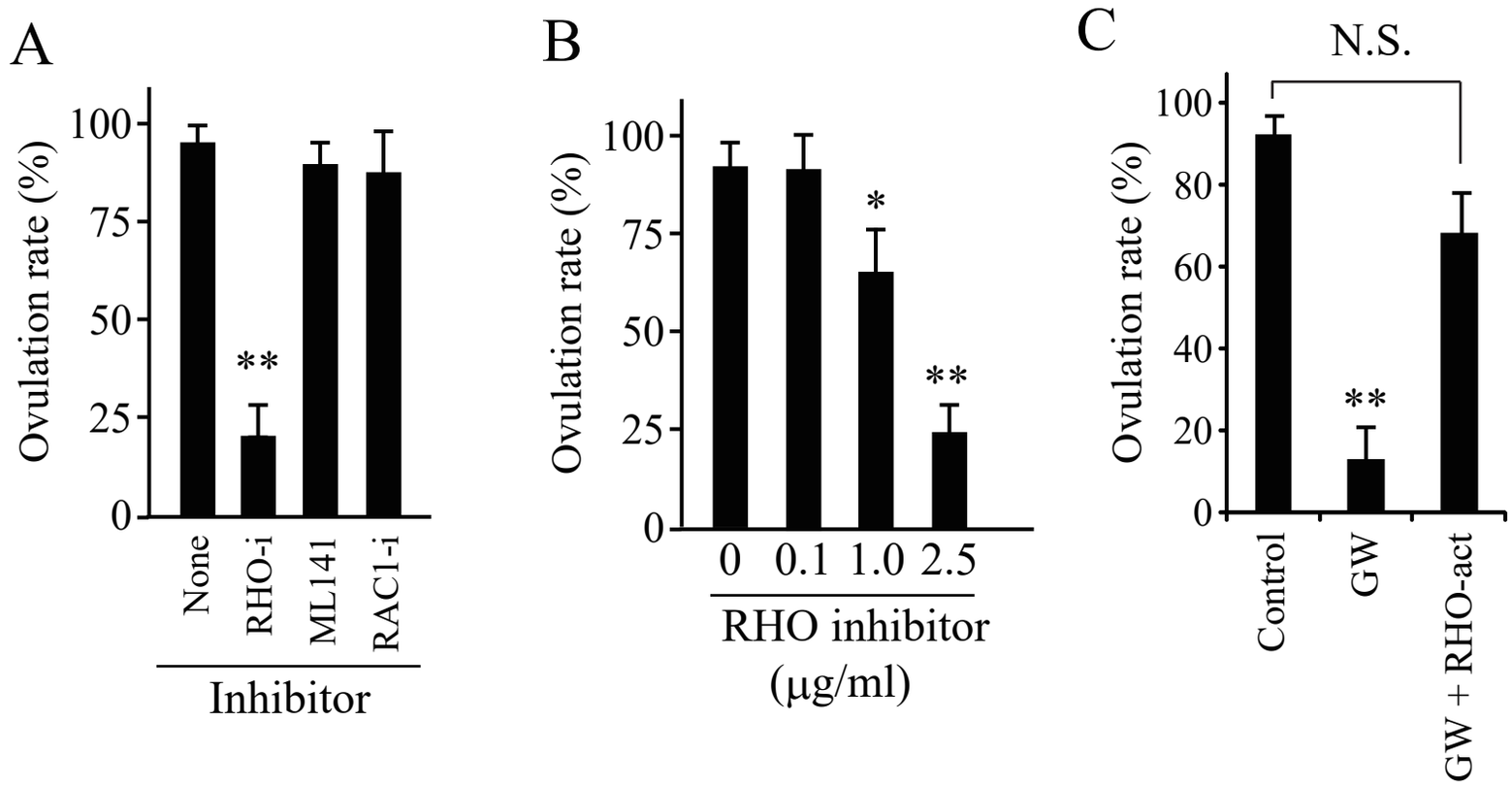
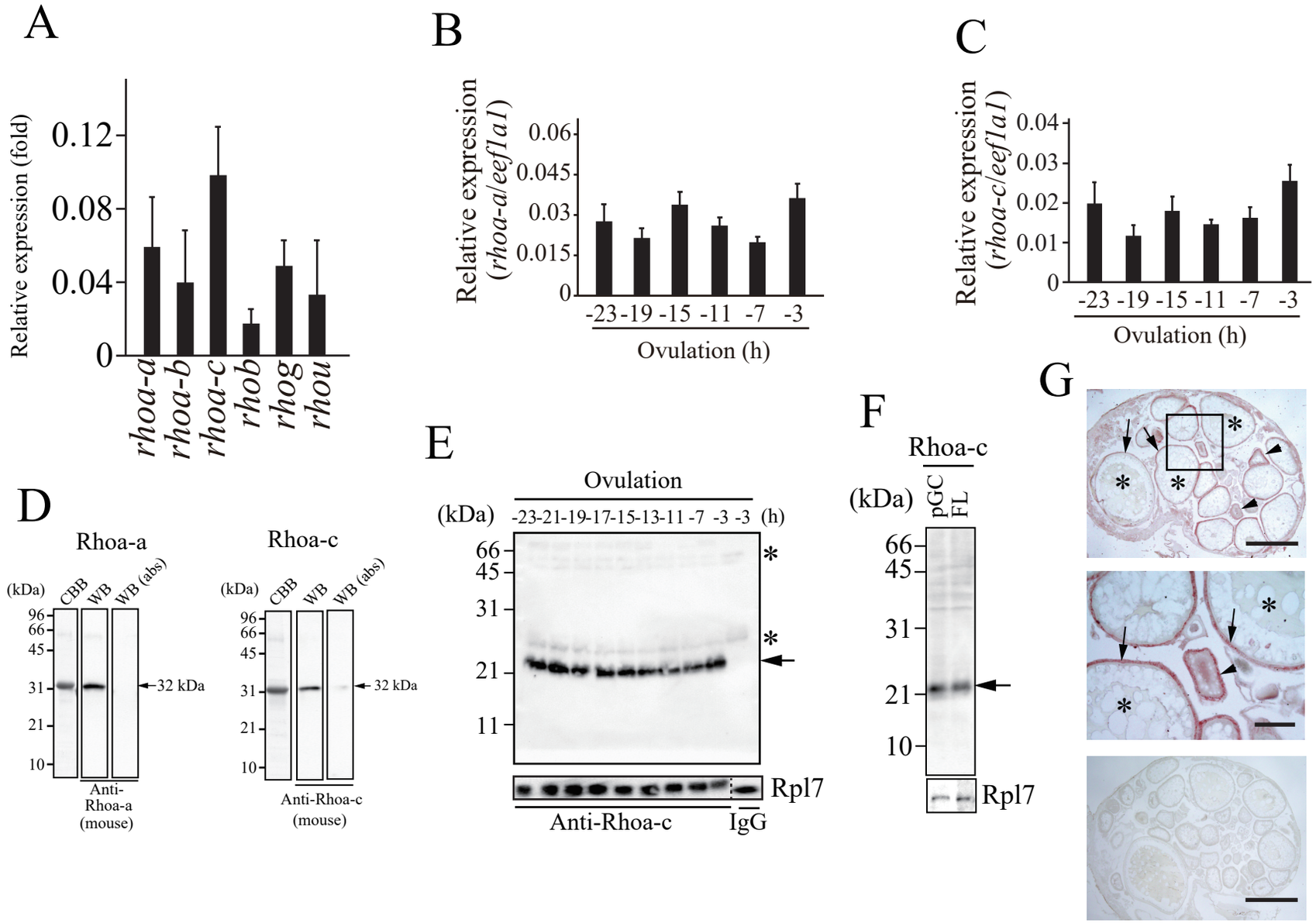

A
Ovulation rate (%)
100
75
50
25
0
**
None
RHO-i
ML141
RAC1-i
Inhibitor
B
Ovulation rate (%)
100
75
50
25
0
*
**
0
0.1
1.0
2.5
RHO inhibitor
(μg/ml)
C
N.S.
Ovulation rate (%)
100
80
60
40
20
0
**
Control
GW
GW + RHO-act

Fig. 2


A
Relative expression (fold)
0.12
0.08
0.04
0
rhoa-a
rhoa-b
rhoa-c
rhob
rhog
rhou
B
Relative expression (rhoa-a/eef1a1)
0.06
0.045
0.03
0.015
0
-23 -19 -15 -11 -7 -3
Ovulation (h)
C
Relative expression (rhoa-c/eef1a1)
0.04
0.03
0.02
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-23 -19 -15 -11 -7 -3
Ovulation (h)
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Rhoa-a
(kDa)
CBB
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32 kDa
Anti-Rhoa-a (mouse)
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(kDa)
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F
Rhoa-c
(kDa)
pGC
FL
66
45
31
21
10
Rpl7
G
*
*
*
*
*

Fig. 3

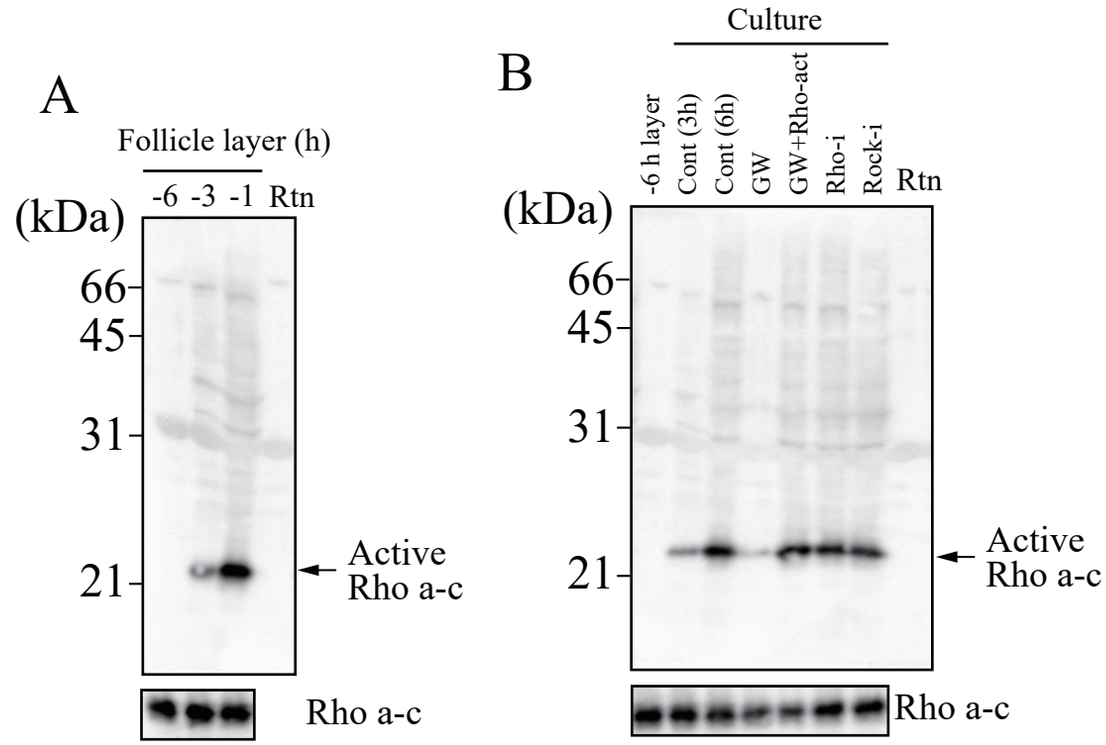

A
Follicle layer (h)
-6 -3 -1 Rtn
(kDa)
66
45
31
21
Active
Rho a-c
Rho a-c
B
Culture
-6 h layer
Cont (3h)
Cont (6h)
GW
GW+Rho-act
Rho-i
Rock-i
Rtn
(kDa)
66
45
31
21
Active
Rho a-c
Rho a-c

Fig. 4

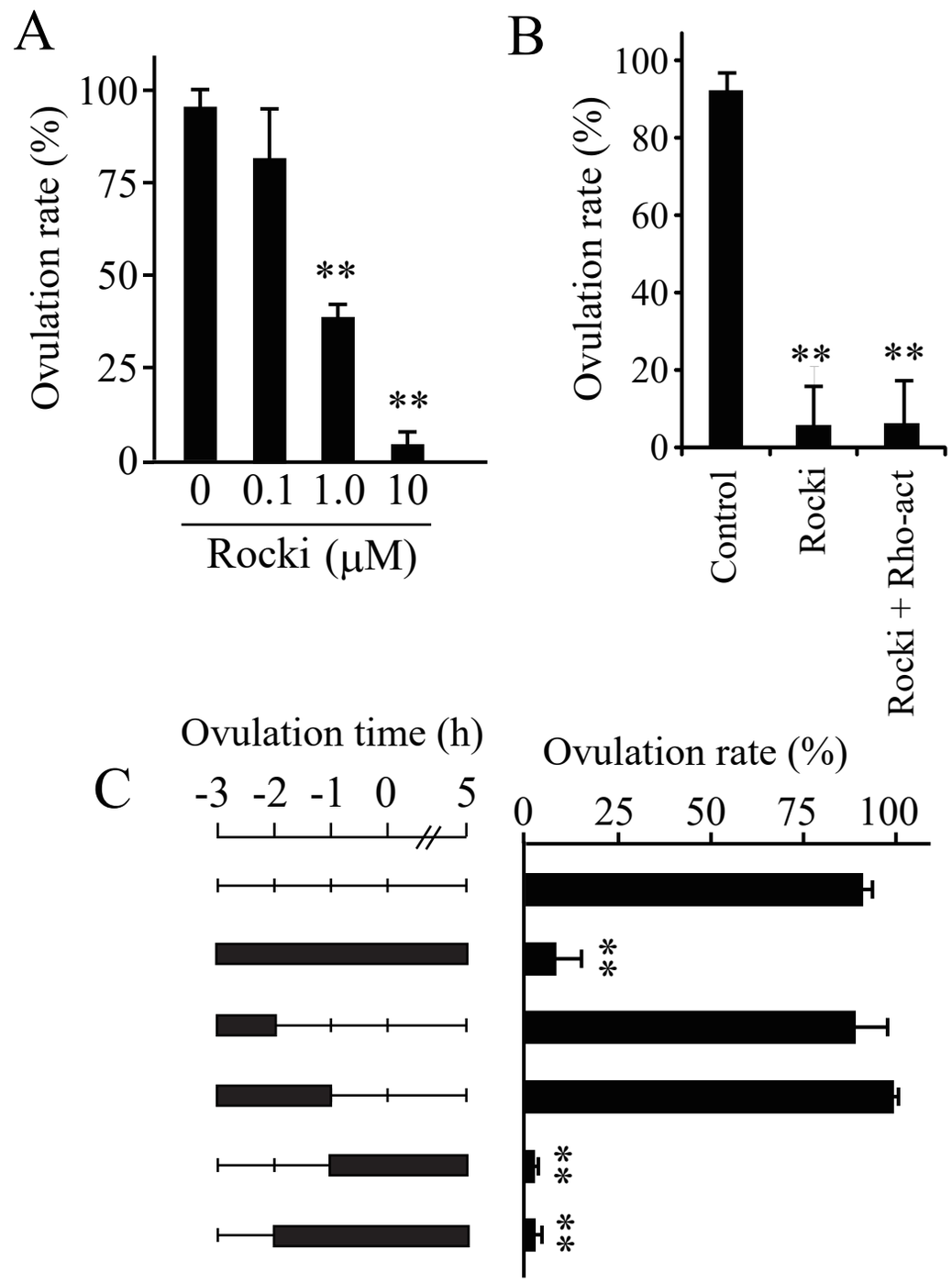

A
Ovulation rate (%)
100
75
50
25
0
**
**
0
0.1
1.0
10
Rocki (μM)
B
Ovulation rate (%)
100
80
60
40
20
0
**
**
Control
Rocki
Rocki + Rho-act
C
Ovulation time (h)
-3
-2
-1
0
5
Ovulation rate (%)
0
25
50
75
100
**
**
**

Fig. 5

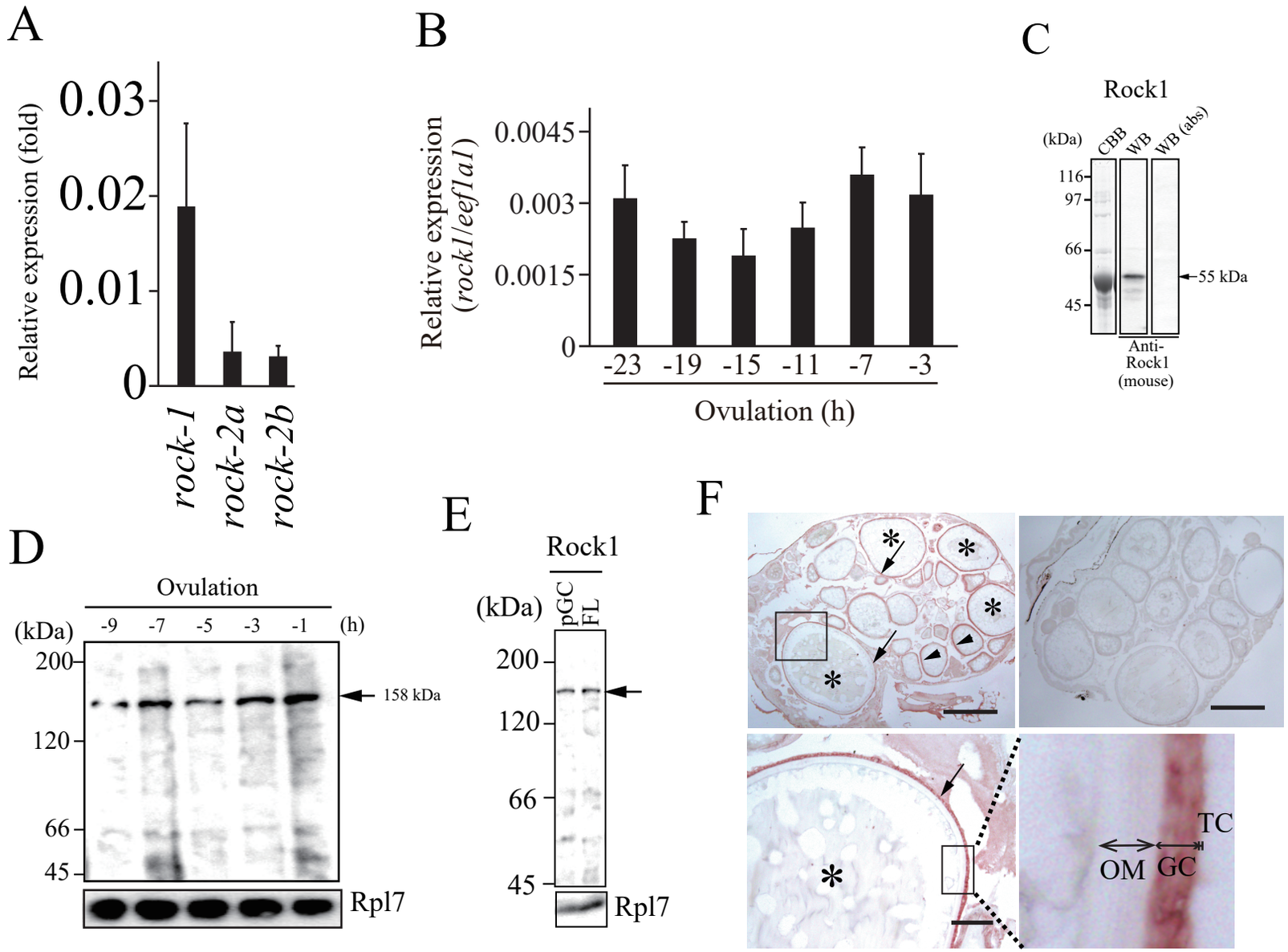
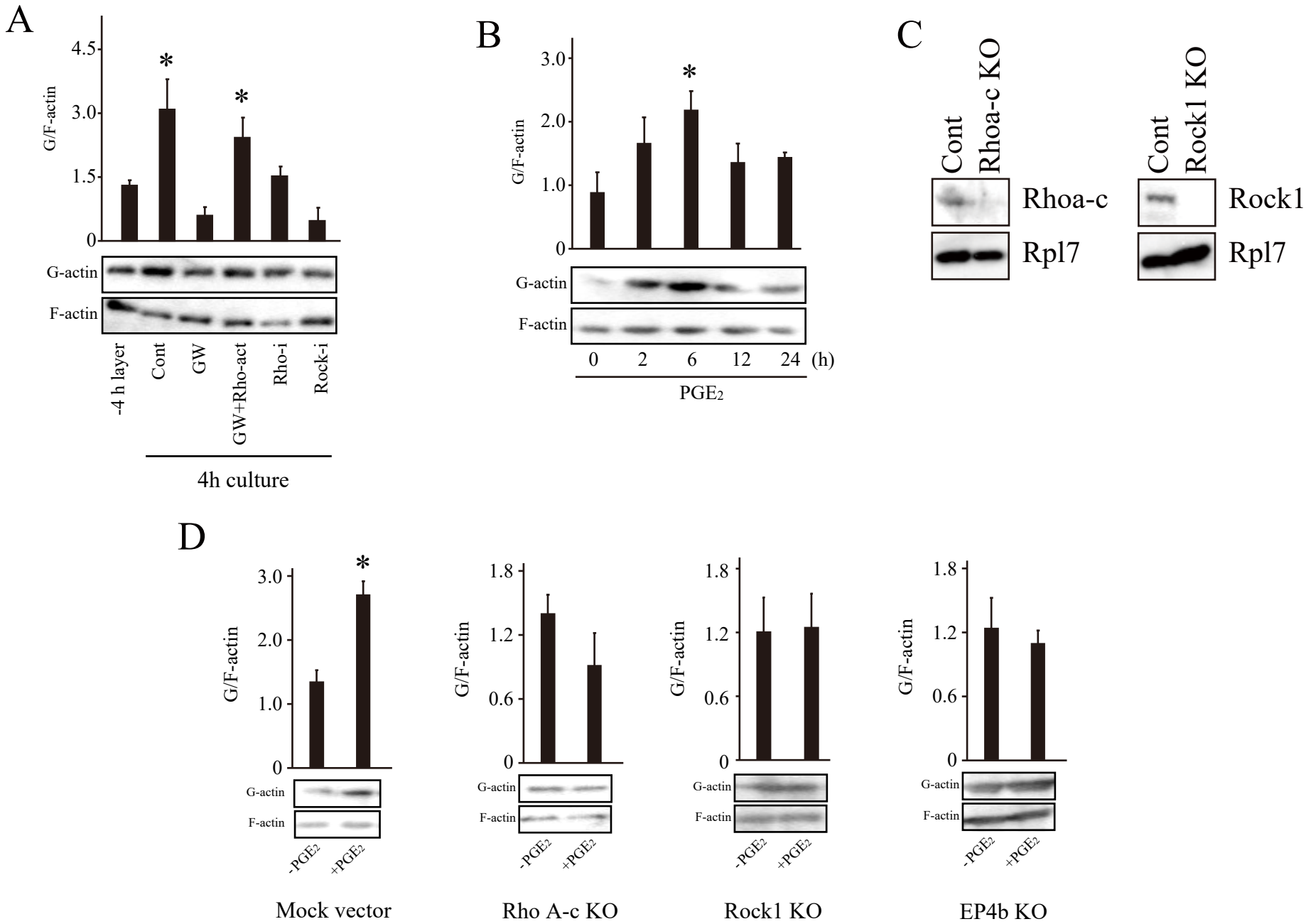

A
Relative expression (fold)
0.03
0.02
0.01
0
rock-1
rock-2a
rock-2b
B
Relative expression (rock1/eef1a1)
0.0045
0.003
0.0015
0
-23
-19
-15
-11
-7
-3
Ovulation (h)
C
Rock1
(kDa)
CBB
WB
WB (abs)
116
97
66
45
55 kDa
Anti-Rock1 (mouse)
D
Ovulation
(kDa)
-9
-7
-5
-3
-1
(h)
200
120
66
45
158 kDa
Rpl7
E
Rock1
(kDa)
pGC
FL
200
120
66
45
Rpl7
F
*
TC
OM
GC

Fig. 6


A
G/F-actin
4.5
3.0
1.5
0
*
*
G-actin
F-actin
-4 h layer
Cont
GW
GW+Rho-act
Rho-i
Rock-i
4h culture
B
G/F-actin
3.0
2.0
1.0
0
*
G-actin
F-actin
0
2
6
12
24
(h)
PGE2
C
Cont
Rhoa-c KO
Rhoa-c
Rpl7
Cont
Rock1 KO
Rock1
Rpl7
D
G/F-actin
3.0
2.0
1.0
0
*
G-actin
F-actin
-PGE2
+PGE2
Mock vector
1.8
1.2
0.6
0
Rho A-c KO
Rock1 KO
EP4b KO

Supplemental Table S1. Primers used in this study.

Primer name	gene	Sequence	Accession No.
Real-time PCR			
Rho A-a ss	*rhoa-a*	5’-CAACGACTGACGCTAACAAAG-3’	XM_004086108
Rho A-a as	*rhoa-a*	5’-CCGACTATGACCAGCTTTTTC-3’	XM_004086108
Rho A-b ss	*rhoa-b*	5’-ACTGCAAGGTCACATACATA-3’	XM_023956423
Rho A-b as	*rhoa-b*	5’-CAGGGAACTGATCCTTACTG-3’	XM_023956423
Rho A-c ss	*rhoa-c*	5’-CTCAGCGAAACGCAGTTAGA-3’	XM_004070475
Rho A-c as	*rhoa-c*	5’-CCCAACAATCACCAACTTCTT-3’	XM_004070475
Rho B ss	*rhob*	5’-CTCCTAGGAAAAGGCAGGAAT-3’	XM_004083452
Rho B as	*rhob*	5’-CTCGTCCCTGCTAAACACAAT-3’	XM_004083452
Rho G ss	*rhog*	5’-ACTCATCCATCAGCATCTAG-3’	XM_004076673
Rho G as	*rhog*	5’-AGGCTCCGGTGGTGTAGGAA-3’	XM_004076673
Rho U ss	*rhou*	5’-GTTCTGGTCGGGACACAGTG-3’	XM_004067248
Rho U as	*rhou*	5’-TCCGATCTCCACTGCACAAT-3’	XM_004067248
Rock1 ss	*rock1*	5′-TCTCTGGTTGGGACTTACAG-3′	XM_004079418
Rock1 as	*rock1*	5′-GCAGACTCTCCAGATGACTT-3′	XM_004079418
Rock2a ss	*rock2a*	5′-TGGAGGACATGCTCAGAGAC-3′	XM_023951816
Rock2a as	*rock2a*	5′-CGTAGCGCCGGGTAGTCCAA-3′	XM_023951816
Rock2b ss	*rock2b*	5′-AGGCCTTCCTCAACAGATAT-3′	XM_023952796
Rock2b as	*rock2b*	5′-CCAGCTGTACTTCTCCAAAT-3′	XM_023952796
EF1a SS	*eef1a*	5′-CACCGGTCACCTGATCTACA-3′	AB013606
EF1a AS	*eef1a*	5′-GCTCAGCCTTGAGTTTGTCC-3′	AB013606
Recombinant protein			
RhoA-a pET SS	*rhoa-a*	5’-ATGGCAGCGATCAGGAAAAAG-3’	XM_004086108
RhoA-a pET AS	*rhoa-a*	5’-TTACAGTAGGACGCATCTATT-3’	XM_004086108
RhoA-c pET SS	*rhoa-c*	5’-ATGGCCGCACTCAGAAAGAAG-3’	XM_004070475
RhoA-c pET AS	*rhoa-c*	5’-TCACAGTAGCTGGCAGCCCCC-3’	XM_004070475
Rock1 pET SS	*rock1*	5’-ATGTCCTCCGAGATAAACATG-3’	LC726226
Rock1 pET AS	*rock1*	5’-TTACAGACTCTCCAGATGACTT-3’	LC726226
Cloning			
Rock1 cds-AS	*rock1*	5′-TTAGCTCAGCTTTCCCGTGTTG-3′	LC726226

Table S1. (continued)

Primer name	gene	Sequence	Accession No.
Crsper-Cas9			
EP4b sgRNA-SS	*ptger4b*	5′-TAGGGAATGTCATCGCCATCG-3′	AB563504
EP4b sgRNA-AS	*ptger4b*	5′-AAACCGATGGCGATGACATTC-3′	AB563504
Rhoa-c sgRNA-SS	*rhoa-c*	5′-TAGGAACTACATTGCTGACATTG-3′	XM_004070475
Rhoa-c sgRNA-AS	*rhoa-c*	5′-AAACCAATGTCAGCAATGTAGTT-3′	XM_004070475
Rock-1 sgRNA-SS	*rock1*	5′-TAGGCTGGATGGCTTGGATGCTC-3′	LC726226
Rock-1 sgRNA-AS	*rock1*	5′-AAACGAGCATCCAAGCCATCCAG-3′	LC726226
RT-PCR			
EP4b-RT-SS	*ptger4b*	5′-CTGTGAGAAGGTCTTCCTAG-3′	AB563504
EP4b-RT-AS	*ptger4b*	5′-CCACCCCCTTACATCTGATT-3′	AB563504
Rhoa-c-RT-SS	*rhoa-c*	5’-ATGGCCGCACTCAGAAAGAAG-3’	XM_004070475
Rhoa-c-RT-AS	*rhoa-c*	5’-TCACAGTAGCTGGCAGCCCCC-3’	XM_004070475
Rock-1-RT-SS	*rock1*	5′-CTGAAGCTCAGCCTCTCTAA-3′	LC726226
Rock-1-RT-AS	*rock1*	5′-TGTCACCGTCAGATCCAACT-3′	LC726226
b-actin-RT-SS	*actb*	5′-CAGACACGTATTTGCCTCTG-3′	D89627
b-actin-RT-AS	*actb*	5′-CAAGTCGGAACACATGTGCA-3′	D89627