# Title page

Title:

Gonadotropin and Oxygen Regulation of Leukemia Inhibitory Factor Secretion from Rhesus macaque Granulosa Cells

Title: State the key point of the manuscript. Indicate the species studied and avoid uncommon abbreviations. Maximum 120 characters including spaces.

**Authors:**

Heather A. Talbott a, Adam Kriega, John S. Davis b,c and Jon Hennebolda

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Affiliations:

a Division of Reproductive and Developmental Sciences, Oregon National Primate Research Center, Oregon Health and Sciences University

a Olson Center for Women’s Health, Department of Obstetrics and Gynecology, University of Nebraska Medical Center

c Veterans Affairs Nebraska Western Iowa Health Care System

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# **Abstract (250 words)**

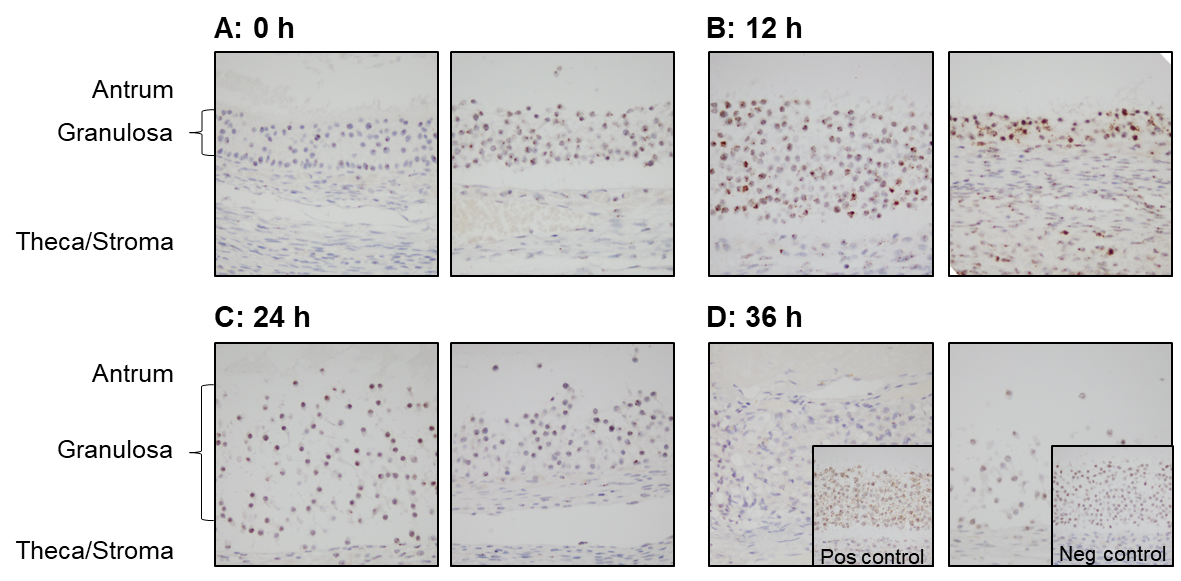
Leukemia inhibitory factor (LIF) is required for rhesus macaque ovulation. However, it is unclear if ovarian granulosa cells are capable of producing LIF and whether additional ovulation-regulating factors impact LIF secretion. Rhesus ovaries collected at 0, 24, and 36 h post-hCG (human chorionic gonadotropin) were assessed by RNAScope for presence and location of LIF mRNA. Culture media was assessed for LIF, vascular endothelial growth factor, and progesterone after culture of primary rhesus non-luteinized and luteinized granulosa cells and KGN cells, a steroidogenic human granulosa-like tumor cell. Culture treatments included hCG (0, 40 IU/mL), follicle stimulating hormone (0, 8.2, or 40 mIU/mL), oxygen (1%, or 20%), LIF (0, or 1 ng/mL for luteinized granulosa cells), and forskolin (0, 1 µM for KGN cells). Granulosa cells of the dominate follicle express peak LIF mRNA levels 24h post ovulatory stimulus, visualized by RNAscope. Rhesus non-luteinized granulosa cells increase LIF secretion in response to hCG (3.4-fold) and FSH (XX-fold). However, luteinized granulosa cells did not secrete LIF either basally or in response to hCG or FSH. Non-luteinized and luteinized granulosa cells both secrete VEGF in response to hCG and FSH. Rhesus non-luteinized granulosa cells increase secretion of LIF when cultured in 1% O2, furthermore LIF secretion increased synergistically (XX-fold) when treated with both hCG and 1% O2.

Rhesus non-luteinized granulosa cells respond to in vitro hCG treatment by: 1) increasing LIF secretion 3.4-fold relative to cells cultured in the absence of hCG, 1%, 2) When non-luteinized granulosa cells were cultured in 1% O2, both basal and hCG-stimulated LIF secretion were increased 1.3-fold compared to 20% O2. The combination of hCG and 1% O2 interacted synergistically to increase LIF secretion. Incubating NLGCs in the presence of both FSH and hCG did not increase LIF or progesterone levels above what was observed when the cells were treated with hCG alone. Thus, in vivo it is likely the granulosa cells are a significant source of the LIF that is found in follicular fluid after an ovulatory stimulus.

# Graphical Abstract

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# Figures and Figure Legends



### Figure 1 – Determination of Ovarian Cell Type Responsible for LIF Secretion

RNAscope analysis of rhesus macaque follicles collected at indicated times after hCG treatment, the ovarian sections were probed for LIF. Panel A: Ovaries collected prior to hCG administration, Panel B: ovaries collected 12 h after hCG treatment, Panel C: ovaries collected 24 h after hCG. Panel D: ovaries collected 24 h after hCG, insets show positive control probe (PPIB, cyclophilin B), and negative control probe (DapB, only found in bacteria).



### Figure 2 – Gonadotropin regulation of rhesus macaque granulosa cells

Nonluteinized granulosa cells (left panels) and 36 h luteinized granulosa cells (right panels) cultured for 24 h at 20% O2 with 0 IU/mL hCG or 40 IU/mL and 0, 0.5, or 2.5 ng/mL FSH. Panel A: LIF concentrations in culture media (pg/mL). Panel B: VEGF concentrations (pg/mL). Panel C: Progesterone concentrations. Panel D: Normalized mRNA expression of hCG treatment marker HSD3B2, note the different scales for non-luteinized and luteinized granulosa cells. Scatterplots of values are superimposed on bar graphs indicating condition mean, 0 IU/mL hCG (●), 40 IU/mL hCG (○), n = 4. Significance was determined using three-way ANOVA with matching, α = 0.05

P-values determined for main effects and interactions of nonluteinized granulosa cells: LIF (FSH = 0.006, hCG = 0.03, FSH x hCG = 0.11), VEGF (FSH = 0.002, hCG = 0.004, FSH x hCG = 0.005), progesterone (FSH = 0.007, hCG = 0.02, FSH x hCG = 0.01), and HSD3B2 mRNA (FSH = ?, hCG = ?, FSH x hCG = ?). P-values determined for main effects and interactions of luteinized granulosa cells: LIF (FSH = 0.9, hCG = 0.3, FSH x hCG = .2), VEGF (FSH = <0.0001, hCG = 0.02, FSH x hCG = 0.007), progesterone (FSH = 0.1, hCG = <0.0001, FSH x hCG = 0.02), and HSD3B2 mRNA (FSH = ?, hCG = ?, FSH x hCG = ?).

Conditions that differ significantly are labeled with no letters in common, significance determined by Tukey’s multiple comparisons test, α = 0.05.

### Figure 3 – Oxygen regulation of rhesus macaque granulosa cells



Nonluteinized granulosa cells (NLGC, left panels) and 36 h luteinized granulosa cells (LGC, right panels) cultured for 24 h at 20% O2 or 1% O2 with 0 or 40 hCG (IU/mL). Panel A: Culture media concentration of LIF (pg/mL). Panel B: Culture media concentration of VEGF (pg/mL). Panel C: Progesterone concentration in culture media. Panel D: Normalized mRNA expression of hypoxia marker KDM3A. n = 4

### Figure 4 – Gonadotropin and oxygen regulation of KGN human granulosa tumor cell line



KGN cells cultured for 24 h at 20% O2 or 1% O2 with 0 or 40 hCG (IU/mL). Panel A: Culture media concentration of LIF (pg/mL). Panel B: Progesterone concentration in culture media. Panel D: Normalized mRNA expression of hypoxia marker KDM3A and hCG treatment marker HSD3B2.

### Figure 5 – LIF regulation of rhesus macaque granulosa cells



Nonluteinized granulosa cells (NLGC, left panels) and 36 h luteinized granulosa cells (LGC, right panels) cultured for 24 h with 0 or 1 ng/mL LIF at 20% O2 or 1% O2 with 0 or 40 hCG (IU/mL). Panel A: VEGF concentration (pg/mL) in culture media. Panel B: Progesterone concentration in culture media. Panel C: Normalized mRNA expression of LIF treatment marker SOCS3. Panel D: Normalized mRNA expression of hypoxia marker KDM3A and hCG treatment marker HSD3B. n = 4

# Introduction

Luteinizing hormone (LH) stimulates ovulation and induces an inflammatory-type reaction in the follicle, which is necessary for fertility. During ovulation, LH induces secretion of critical intrafollicular factors, which notably include inflammatory cytokines. However, the functional roles for most ovulation-associated cytokines are unknown in non-human primates and humans. There is a critical need to determine the function of LH-stimulated follicular cytokines in order to determine essential pathways for ovulation that could serve as targets for regulation of female fertility.

Follicular LIF levels increase 15-fold in rhesus macaques [1] and humans [2] after an ovulatory stimulus. We determined that the complete canonical LIF-signaling pathway is present in the rhesus macaque follicle during ovulation [3]. Members include the LIF receptor, co-receptor (gp130), and the LIF-activated transcription factor STAT3 (signal transducer and activator of transcription 3). Most notably, LIF signaling is required for rhesus macaque ovulation, which our laboratory recently published [1]. Although LIF follicular concentrations are positively correlated with embryo quality, the downstream functional LIF effects are unknown in the follicle.

Thus, the objective of this study was to determine factors that promote LIF signaling in rhesus macaque granulosa cells. The hypothesis was that secretion of the cytokine leukemia inhibitory factor (LIF) was regulated by processes known to be important for ovulation, specifically LHCGR activation and low oxygen tension. Additionally, LIF activates canonical inflammatory transcription factors and modulates progesterone biosynthesis in the rhesus macaque follicular granulosa cells.

# Materials and Methods

## Animal Protocols

All animal protocols have been previously described in detail including the housing and general care of rhesus macaques(*Macaca mulatta*) [4], monitoring of serum hormone levels [1], controlled ovulation [5], controlled ovarian stimulation [6], and rhesus granulosa cell culture [7,8]. Briefly, definitions and key parameters are described.

Controlled ovulation allows for the selection and development of a single follicle and allows for precision treatment of ovulatory stimuli and subsequent collection of the follicle. Ovaries were collected from animals at 12 h, 24 h, and 36 h after hCG administration; as well, ovaries were collected from animals that did not receive hCG (0 h).

IUCAC Approvals:

## Statistics

# Results

## Visualization and quantification of luteal tissue LDs

# Discussion

# Acknowledgments

Individuals who have provided important contributions, such as reagents, services, editorial assistance or conceptual advice, to the research described in the manuscript but are not co-authors should be acknowledged here. List funding support on the title page.

# Conflict of interest

Provide a statement indicating any potential or actual conflicts of interest with respect to the work reported in the article.

# Author contributions

Indicate the contributions to the manuscript made by each author, identified by initials corresponding to first and last names.

# References

# Tables

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