



SARS-CoV-2 infection negatively affects ovarian function in ART patients

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ABSTRACT

Several organs, such as the heart, breasts, intestine, testes, and ovaries, have been reported to be target tissues of the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) infection. To date, no studies have demonstrated SARS-CoV-2 infection in the female reproductive system. In the present study, we investigated the effects of SARS-CoV-2 infection on ovarian function by comparing follicular fluid (FF) from control and recovered coronavirus disease 2019 (COVID-19) patients and by evaluating the influence of these FF on human endothelial and non-luteinized granulosa cell cultures. Our results showed that most FFs (91.3%) from screened post COVID-19 patients were positive for IgG antibodies against SARS-CoV-2. Additionally, patients with higher levels of IgG against SARS-CoV-2 had lower numbers of retrieved oocytes. While VEGF and IL-1 β were significantly lower in post COVID-19 FF, IL-10 did not differ from that in control FF. Moreover, in COV434 cells stimulated with FF from post COVID-19 patients, steroidogenic acute regulatory protein (StAR), estrogen-receptor β (Er β), and vascular endothelial growth factor (VEGF) expression were significantly decreased, whereas estrogen-receptor α (ER α) and 3 β -hydroxysteroid dehydrogenase (3 β -HSD) did not change. In endothelial cells stimulated with post COVID-19 FF, we observed a decrease in cell migration without changes in protein expression of certain angiogenic factors. Both cell types showed a significantly higher γ H2AX expression when exposed to post COVID-19 FF. In conclusion, our results describe for the first time that the SARS-CoV-2 infection adversely affects the follicular microenvironment, thus dysregulating ovarian function.

1. Introduction

Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has spread throughout the world. As of June 14, 2021, more than 175 million cases and 3.7 million deaths are attributed to this virus worldwide. In Argentina, around 3.48 million cases were confirmed with 73,391 reported deaths (1,2).

SARS-CoV-2 invades the target cell by binding to angiotensin-converting enzyme 2 (ACE-2). The viral entry is further processed by

the transmembrane serine protease 2 (TMPRSS2), thus allowing the fusion of the cell membranes of virus and host cell (3). It is public knowledge that SARS-CoV-2 can cause severe damage, particularly in the respiratory system (4). The most frequently observed symptoms in COVID-19 patients include fever, cough, and pneumonia. However, other symptoms such as thrombosis, pulmonary embolism, and high blood pressure have been reported as well, suggesting that the virus targets the endothelium (5,6). It is well known that ACE-2 is also expressed in endothelial cells (7,8). Additionally, dysregulated immune

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responses, as those observed in COVID-19, are a major culprit in endothelial dysfunction, since they alter microvascular permeability and induce vascular inflammation (6). Nonetheless, other organs such as the heart, breasts, intestine, testes, and ovaries have also been reported to be target tissues of this viral infection (9,10). To date, no studies have presented evidence of SARS-CoV-2 infecting the female reproductive system.

ACE-2 is expressed in the uterus, vagina, placenta, and ovary (11,12). In particular, ACE-2 mRNA transcripts have been detected in ovaries from reproductive-age and postmenopausal women. Both stromal and granulosa cells have been found to be positive for ACE-2 in the human ovary (13). Furthermore, ACE-2 expression in rat and bovine granulosa cells is regulated by gonadotropic hormones (14,15). Whether this virus binds to ACE-2 receptors in the ovary and which effects, if any, this infection would have on ovarian function and oocyte quality remains unclear. Nevertheless, to the best of our knowledge, no reports have addressed the consequences of COVID-19 on ovarian function.

During the final stages of folliculogenesis, the oocyte is localized in an antral follicle in the ovary. The female gamete is exposed to a microenvironment that includes follicular fluid (FF) and somatic cells (namely granulosa and theca cells) within the follicle. The composition of FF differs from that of serum—it is a complex mixture of hormones, cytokines, metabolites, and other proteins secreted mainly by granulosa cells (16,17). FF composition reflects the stage of oocyte development and oocyte quality (18,19). Therefore, an altered FF composition is associated with a reduced reproductive function.

Based on these considerations, we hypothesized that the SARS-CoV-2 infection can potentially affect ovarian function, disturbing the follicular microenvironment and thus affecting oocyte quality in recovered women. Hence, we evaluated the presence of SARS-CoV-2 IgG antibodies and antigens, interleukin-1 β (IL-1 β), interleukin-10 (IL-10), and vascular endothelial growth factor (VEGF) levels in FF from healthy and recovered SARS-CoV-2 women undergoing assisted reproductive technology (ART) procedures. We also examined the effect of FFs obtained from the above-mentioned patients on: a) the proliferation, migration, angiopoietins 1 and 2 (ANGPT-1/2), and VEGF expression of a human endothelial cell culture; and b) the proliferation and protein expression of estrogen-receptor α (ER α) and β (ER β), steroidogenic acute regulatory protein (StAR), 3 β -hydroxysteroid dehydrogenase (3 β -HSD), and VEGF in human non-luteinized granulosa cells. Additionally, we analyzed the effect of FFs on nuclear DNA damage in both cell types.

2. Materials and methods

2.1. Ethical approval

This study was approved by the ethics committee of the Instituto de Biología y Medicina Experimental (IBYME-CONICET; Study No. 2850). Written informed consent was given by all patients before recruitment.

2.2. Study population and FF collection

For this study, we enrolled a total of 80 women (21–41 years old) undergoing assisted reproductive technology procedures between November 2020 and April 2021 at PREGNA Medicina Reproductiva (Buenos Aires, Argentina), IVI Buenos Aires (Buenos Aires, Argentina), Fertilis (Buenos Aires, Argentina) and InVitro (Buenos Aires, Argentina). Patients with pathologies such as uterine fibroids, endometriosis, pelvic inflammatory disease, premature ovarian failure, and PCOS were excluded from the study. Additionally, we excluded patients with poor ovarian response (less than three antral follicles). The patients were classified into two groups: control patients ($n = 34$), who had never tested positive for COVID-19 or experienced any COVID-related symptoms, and post COVID-19 patients ($n = 46$), who had at least one positive PCR test for COVID-19 but were given medical clearance before starting the fertility treatment. The patients in this group were asymptomatic or

presented mild symptoms such as anosmia, dysgeusia, and flu-like symptoms (fever, sore throat, and cough) (20–22).

The time interval between the infection of the patients with SARS-CoV-2 and the retrieval of FF varied between 2 and 9 months, the average being 4.5 months. None of the patients were vaccinated against COVID-19 prior to the study. A protocol for ovarian stimulation was assigned to patients according to their ovarian reserve and following the standard protocol of each clinic. In all cases, it consisted of a gonadotropin protocol (recombinant FSH, highly purified human menopausal gonadotropin, or a combination of both) for an average of 10 days (range, 9–12 days). Ovulation was induced by subcutaneous administration of a GnRH agonist or hCG. All patients were included in the statistical analysis, since there were no differences between the parameters studied in either group receiving GnRH α or hCG trigger for ovulation.

Oocyte retrieval was conducted under vaginal ultrasound guidance 34–36 h after ovulation induction. Human FF was extracted from all 16- to 20-mm follicles of each patient. No flush was used after the aspiration of all accessible ovarian follicles. Only macroscopically clear fluids, indicating lack of contamination and blood, were considered in the study. Immediately after oocyte removal, the FF was centrifuged for 10 min at 2000g to remove cellular components and debris. Once transferred to sterile polypropylene tubes, the supernatant was stored at -20°C until assayed. For *in vitro* experiments we selected randomly 20 patients per group, and each patient's FF was used individually. The biochemical analyses were performed in the *Laboratory for Studies of the Physiopathology of the Ovary* at IBYME-CONICET (www.ibyme.org.ar/laboratorios/51/estudios-de-la-fisiopatologia-del-ovario).

Serum samples for estradiol determination were obtained on the day of the ovulation trigger. Basal hormone levels prior to ovarian stimulation (estradiol, progesterone, and prolactin) were obtained from the patients' clinic history, when available. Various parameters were used to evaluate the efficacy of ovarian stimulation, including the numbers of retrieved cumulus–oocyte complexes and of mature oocytes that reached metaphase II (MII). In addition, each group of patients (control and post COVID-19) was divided into two subsets according to age as follows: control; ≤ 35 ($n = 19$) and > 35 ($n = 15$) and post COVID-19 ≤ 35 ($n = 22$) and > 35 ($n = 24$), respectively. The analyses of ovarian stimulation outcomes were duplicated for each subset.

2.3. Immunoassays

The levels of SARS-CoV-2 IgG in FF samples were measured using an enzyme-linked immunosorbent assay (ELISA) designed specifically to measure immunoreactive IgG against SARS-CoV-2 in human fluids (COVIDAR IgG, Argentina) (23). This kit, which was generously donated by Dr. Andrea Gamarnik (Fundación Instituto Leloir-CONICET, Buenos Aires, Argentina), uses two viral proteins as antigens—a trimer stabilized spike protein and the receptor binding domain (RBD). The presumed presence or absence of specific IgG antibodies against the SARS-CoV-2 virus was analyzed taking into account the cut-off value, which was defined as the mean optical density (OD) of the negative control $+0.2$, according to the manufacturer's instructions. We classified the level of immunoreactivity in each patients' FF based on their absorbance values: low (between 0.22 and 0.5), medium (between 0.5 and 1), and high (greater than 1).

The presence of SARS-CoV-2 viral antigens in FF was determined using the Panbio™ COVID-19 Ag Rapid Test Device (Abbott Diagnostics, Jena, Germany) following manufacturer's instructions.

VEGF concentrations in FF were measured with a commercial ELISA kit (Catalog# 900-TM10; Peprotech, NJ, United States), according to the manufacturer's instructions. IL-1 β and IL-10 concentrations in FF were measured using commercial kits (IL-1 β Catalog# 557953; IL-10 Catalog# 555157; BD Biosciences, CA, United States), as previously described by Gori et al. (24).

Table 1
Clinical information of control patients and post COVID-19 patients.

Baseline characteristics of patients	Control patients (n = 34)			Recovered COVID-19 patients (n = 46)			P value
	Mean	Min–Max	SEM	Mean	Min–Max	SEM	
Age (years)	33.09	23–38	0.60	33.43	21–44	1.02	n.s.
Number of oocytes retrieved in patients ≤ 35 years	11.84	8–23	0.85	13.80	0–30	2.21	n.s.
Number of oocytes retrieved in patients > 35 years	11.11	6–16	0.95	6.95	0–15	0.95	0.0187
MII oocytes (n, %)	9.03 (79.84%)	6–16	0.61	11.98 (82.23%)	0–30	1.41	n.s.
Basal serum estradiol (pg/ml)	33.00	19–46	7.81	42.70	25–56	3.45	n.s.
Serum estradiol on trigger day (pg/ml)	2710	400–5772	576.9	1424	325–3728	1152	n.s.
Basal serum progesterone (ng/ml)	1.09	0.52–1.86	0.18	1.37	0.30–4.38	0.58	n.s.
Basal serum prolactin (ng/ml)	20.37	6.20–48	3.01	15.74	1–36.20	1.83	n.s.
AMH (ng/ml)	2.067	0.5–4.4	0.32	2.917	0.31–5.7	0.48	n.s.
Antral follicles count (AFC)	12.64	7–20	0.77	12.50	4–22	0.99	n.s.
BMI	23.43	18.70–31	0.98	23.01	18–29.36	0.55	n.s.
Time from COVID-19 infection (months)	–	–	–	4.5	2–9	0.37	–

Data are expressed as the mean ± standard error of the mean. Student's *t*-test was used for comparisons between groups. Statistical significance was defined as $p < 0.05$.

from post COVID-19 and control patients (Table 2). The results revealed that 91.3% (42/46) of the FF from post-COVID-19 patients were positive for IgG against SARS-CoV-2, whereas antibodies were not detected in any of the FF from control patients, as expected. Within the post COVID-19 group, the ELISA assay yielded different colorimetric intensities, indicating varying levels of SARS-CoV-2 IgG, which we classified as high (38.1%; 16/42 patients), medium (38.1%; 16/42 patients) and low (23.8%; 10/42 patients). We found no correlation between SARS-CoV-2 IgG levels and the time from infection. We then evaluated the number of retrieved oocytes in each group and found that this parameter significantly decreased with higher titers of SARS-CoV-2 IgG antibodies (low vs. medium, $p < 0.05$; low vs. high, $p < 0.01$). Similar results were obtained for the number of mature oocytes (those that reached MII stage) from each patient (low vs. medium and high, $p < 0.05$). These findings are shown in Fig. 1 A-B. Additionally, we assessed the presence of SARS-CoV-2 viral antigens in FF from patients, but none of the samples presented positive results (data not shown).

3.3. VEGF, IL-1 β , and IL-10 concentration in FF from control and post COVID-19 patients

As shown in Fig. 2 A-B, IL-1 β and VEGF concentrations were significantly lower in FF from post COVID-19 patients than those in FF from control patients (IL-1 β : $p < 0.0001$, VEGF: $p < 0.05$). In contrast, the levels of IL-10 from post COVID-19 FF did not differ significantly from those in control FF (Fig. 2 C). Furthermore, no association was found between the IL-1 β and VEGF levels in FF from post-COVID-19 patients and the time elapsed from the viral infection to the day of oocyte retrieval (data not shown).

Table 2
Detection of IgG antibodies against SARS-CoV-2 by ELISA in control and recovered COVID-19 patients.

Immunoreactivity	Negative (%)	Positive (%)		
		Low-IgG (%)	Medium-IgG (%)	High-IgG (%)
Control FF (n = 34)	34/34 (100%)	–	–	–
Post COVID-19 FF (n = 46)	4/46 (8.7%)	10/42 (23.8%)	16/42 (38.1%)	16/42 (38.1%)

Of the 46 post COVID-19 patients, 91.30% tested positive for IgG antibodies against SARS-CoV-2 in FF. The titer of SARS-CoV-2 IgG antibodies in FF were classified according to their absorbance values as high (greater than 1), medium (between 0.5 and 1), and low (between 0.22 and 0.5).

3.4. Effects of FF from control and post COVID-19 patients on granulosa cell culture

To evaluate whether granulosa cells could be affected by FF from recovered COVID-19 patients, we stimulated COV434 cells with control or post COVID-19 FF. As illustrated in Fig. 3 A-B, the analysis of endocrine-related proteins showed a significant decrease of STAR and ER β in granulosa cells stimulated with post COVID-19 FF compared with those stimulated with control FF ($p < 0.05$). Protein expression of ER α and 3 β -HSD remained unchanged between both groups (Fig. 3 C–D).

Since VEGF is one of the most important angiogenic factors in the ovary, we measured VEGF protein expression in COV434 by Western blot. The densitometric analysis showed that granulosa cells stimulated with FF from post COVID-19 patients expressed lower levels of VEGF than those stimulated with FF from control patients ($p < 0.05$) (Fig. 3 E).

To study the impact of stimulation with FF from recovered COVID-19 patients on granulosa cells, we evaluated the protein expression of γ H2AX, a molecular marker for DNA damage. The results showed that γ H2AX expression in COV434 cells incubated with post COVID-19 FF was significantly higher than that in cells incubated with control FF ($p < 0.05$) (Fig. 3 F).

Finally, in order to determine whether FF from recovered COVID-19 patients altered granulosa cell proliferation, we quantified this parameter using WST-1. No differences were found in COV434 proliferation rates between the groups (data not shown).

3.5. Effect of FF from control and post COVID-19 patients on endothelial cell culture

To analyze the specific effect of COVID-19 infection on ovarian angiogenesis, migration was quantified in EA.hy926 cells stimulated with FF from control and post COVID-19 patients using a wound healing assay. After 12 h, results showed that FF from post COVID-19 patients significantly decreased endothelial cell migration compared with FF from control patients ($p < 0.0001$) (Fig. 4 A-B). In addition, we analyzed ANGPT-1 and ANGPT-2 protein expression in endothelial cells and no changes were found between groups (Fig. 4 C-E), as well as in VEGF protein levels when cells were stimulated with either control or post COVID-19 FF (Fig. 4 F).

Furthermore, we studied the effect of FF from recovered COVID-19 patients on DNA damage, as determined by endothelial cell expression of γ H2AX. Protein levels of γ H2AX in EA.hy926 cells incubated with FF from post COVID-19 patients were significantly higher than in those with FF from control patients ($p < 0.01$) (Fig. 4 G). Lastly, we evaluated whether endothelial cell proliferation was affected by the presence of FF from recovered COVID-19 patients, but no differences were found between both groups (data not shown).

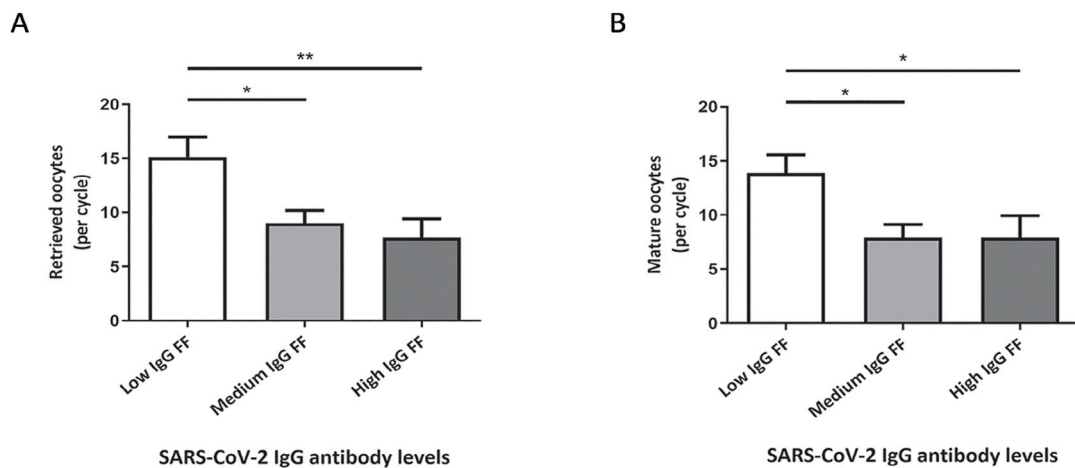


Fig. 1. Retrieved and mature oocytes from patients with low-, medium- and high-level SARS-CoV-2 IgG antibodies in FF. (A) The number of retrieved oocytes was significantly lower in the post COVID-19 subgroups as levels of SARS-CoV-2 IgG were higher (low vs. medium, * $p < 0.05$; low vs. high, ** $p < 0.01$). (B) Similar results were obtained for the number of mature oocytes (low vs. medium and high, * $p < 0.05$).

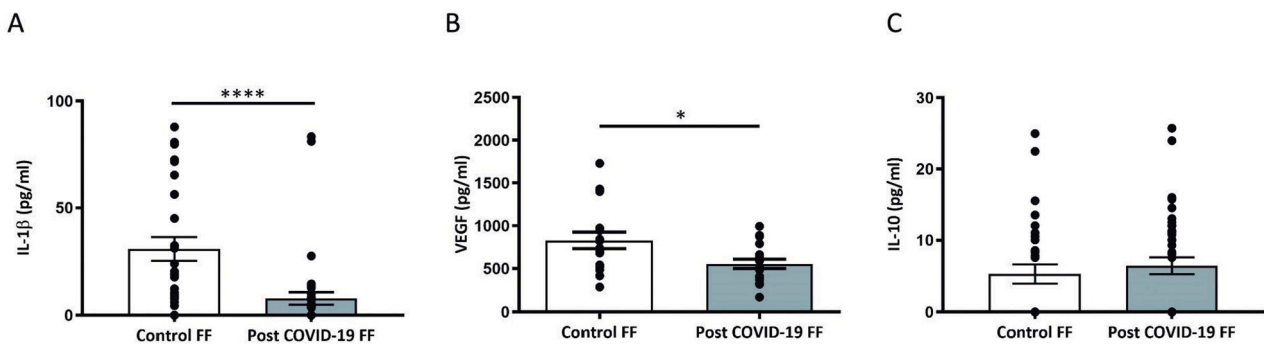


Fig. 2. VEGF, IL-1β and IL-10 concentration in control and post COVID-19 FF determined by ELISA. IL-1β (A) and VEGF(B) concentrations were decreased in FF from post COVID-19 compared with that in FF from control patients (VEGF: * $p < 0.05$, IL-1β: **** $p < 0.0001$). No differences were found between groups in terms of IL-10 levels (C) ($p = 0.4$).

4. Discussion

The data presented in this study demonstrate for the first time the presence of IgG antibodies against SARS-CoV-2 in FF from recovered COVID-19 patients undergoing ART treatments. Additionally, we demonstrated that VEGF and IL-1β levels in FF from post COVID-19 patients were decreased compared with those in the control group (patients that were never infected with SARS-CoV-2). FF contributes to maintaining the controlled microenvironment required to support female gamete development and is composed of a complex mixture of proteins, metabolites, and cytokines. Based on these considerations, several biochemical characteristics of the FF may determine oocyte quality and thus influence the potential reproductive performance.

In our study, in addition to detecting antibodies against SARS-CoV-2, we found that the numbers of retrieved oocytes as well as the mature oocytes were lower in the subgroups with higher SARS-CoV-2 IgG levels. Recently, Peghin et al. (2021) have indicated that the persistent high titers of the serological response against SARS-CoV-2 might play a crucial role as an independent risk factor for severe post COVID-19 symptoms, in addition to gender and the number of symptoms at onset and ICU admission (31).

A number of studies have reported that the presence of certain pathogens can affect the success of IVF treatments. Cortiñas et al. (2004) and Pacchiarotti et al. (2009) have demonstrated that high levels of anti-*Chlamydia trachomatis* IgG and IgA, both in serum and FF, harm implantation rate in women undergoing IVF (32,33). Therefore, it is reasonable to think that the high titers of SARS-COV-2 IgG antibodies

could alter oocyte number and/or quality. Nonetheless, further research is necessary to elucidate whether the presence of immunoglobulins for SARS-CoV-2 adversely affects the reproductive outcome of women. In particular, the impact of these antibodies in FF on oocyte quality should be further explored and its assessment is beyond the objective of the present work.

Several of the growth factors and interleukins in FF are known to be associated with ovarian response and fertilization rates (17,34,35). The follicles and corpora lutea are able to produce many of these, including numerous angiogenic factors. This is especially relevant since a functional ovarian microvasculature is crucial to guarantee the supply of cytokines, hormones, and oxygen that make follicular growth and corpus luteum formation possible.

VEGF, one of the central angiogenic factors, plays a key role in the regulation of normal and abnormal angiogenesis in the ovary (36). Inhibition of VEGF expression results in reduced follicle angiogenesis and lack of antral follicle development. In addition, it is well known that VEGF is involved in the ovulatory process. Accordingly, increased expression of VEGF after administration of an ovulatory dose of gonadotropins is correlated with prostaglandin concentration (37). In our study, VEGF levels in FF from recovered COVID-19 patients undergoing in vitro fertility treatments were lower than those in the control group. Decreased VEGF levels could lead to an abnormal development of the ovarian vasculature and, consequently, fail to provide nutrients and hormones to the growing follicles, affecting the oocyte quality.

In the ovary, cytokines and macrophages are intimately involved in follicular development, ovulation, and luteal function. Our study

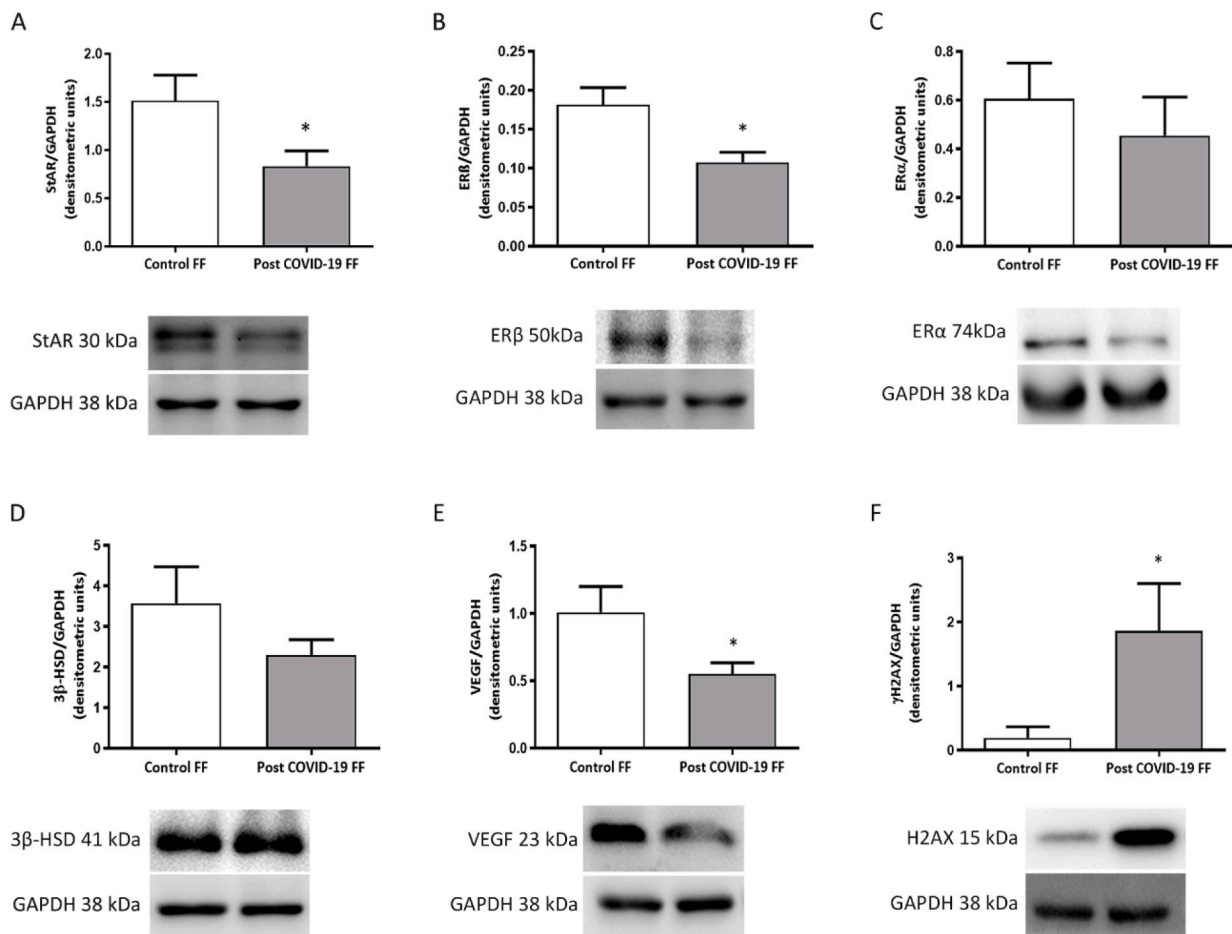


Fig. 3. Effect of FF from post COVID-19 patients on protein expression in granulosa cells. The following proteins were measured by Western Blot: STAR (A); ERβ (B); ERα (C); 3β-HSD (D); VEGF (E); γH2AX (F). Densitometric quantification showed decreased levels of STAR (A; $p < 0.05$) and ERβ (B; $p < 0.05$) in cells stimulated with post COVID-19 FF, whereas protein levels of ERα (C) and 3β-HSD (D) remained unchanged between both groups. VEGF levels were significantly lower ($p < 0.05$) in COV434 cells incubated with FF from post COVID-19 patients compared with those incubated with control FF (E). Ovarian cells stimulated with FF from post COVID-19 patients expressed higher levels of γH2AX than cells stimulated with control FF (F; $p < 0.05$). In all cases, representative immunoblots are shown in the lower panels. Data are expressed as means \pm SEM normalized to GAPDH. Results were obtained from three independent experiments. * $p < 0.05$.

evidenced that IL-1β levels were decreased in FF from recovered COVID-19 patients compared with those in control FF. In particular, it has been reported that IL-1β promotes several processes associated with ovulation, as well as regulates folliculogenesis and atresia (38,39). Intra-ovarian macrophages, which represent from 5 to 15% of the total cellular population in FF (40), are responsible for the production of IL-1β (41), a cytokine that is also secreted by oocytes, theca, and cumulus cells in human ovaries (42–44). Additionally, IL-1β is hormonally regulated and its levels increase during the peri-ovulatory period (45,46). IL-1β, IL-6, and TNFα have been detected in FF of women undergoing in vitro fertilization (47,48), and serum levels of IL-1β positively correlate with estradiol levels on the day of hCG injection (49). Furthermore, Mendoza et al. (2019) demonstrated that increased levels of IL-1β in FF were associated with enhanced fertilization rates (35). Although we did not find any correlation between IL-1β levels and the reproductive outcome in terms of retrieved or mature oocyte numbers, this IL-1β deficiency observed in FF from post COVID-19 patients could have implications for oocyte quality and for prospective reproductive outcomes.

Given that follicles developing healthy oocytes produce high levels of IL-1β and TNFα (35), it is therefore likely that both cytokines are involved in oocyte quality. IL-1β also induces the secretion of TNFα and directly increases vascular permeability (50) and, in turn, TNFα enhances new blood vessel growth during inflammatory processes (51). Based on these data from the literature, it could conceivably be

hypothesized that lower IL-1β levels in post COVID-19 patients decrease TNFα production, which can lead to impaired blood vessel formation in the ovary. This explanation would be consistent with the decrease in VEGF levels observed in post COVID-19 FF. More studies are needed to elucidate the effect of these cytokines on ovarian angiogenesis in recovered COVID-19 patients.

To study the potentially detrimental consequences of altered FF composition in post COVID-19 women, we evaluated the effects of these FF on two pivotal cell types in the ovary—granulosa and endothelial cells. To this purpose, we stimulated a granulosa cell line (COV434) and an endothelial cell line (EA.hy926) with FF from either control or post COVID-19 patients and analyzed endocrine-related proteins, angiogenic markers, and nuclear DNA damage in these cells.

Endocrine-related proteins, such as steroidogenic enzymes and hormone receptors, are essential for ovarian function since follicular development depends on steroid hormone production. Despite being different, these hormones are all synthesized from a common precursor substrate: cholesterol. Since the rate-limiting step in follicular steroidogenesis is the transport of cholesterol to the site of steroid biosynthesis, this makes steroidogenic acute regulatory protein (StAR) a key player. Indeed, the StAR protein predominantly modulates steroid biosynthesis during the folliculogenesis. Furthermore, estrogens and their receptors, α and β, play a crucial role in the pathogenesis of gynecological disorders and/or cancers, i.e., endometriosis as well as breast, endometrial, and ovarian cancers (52,53). In the present study,

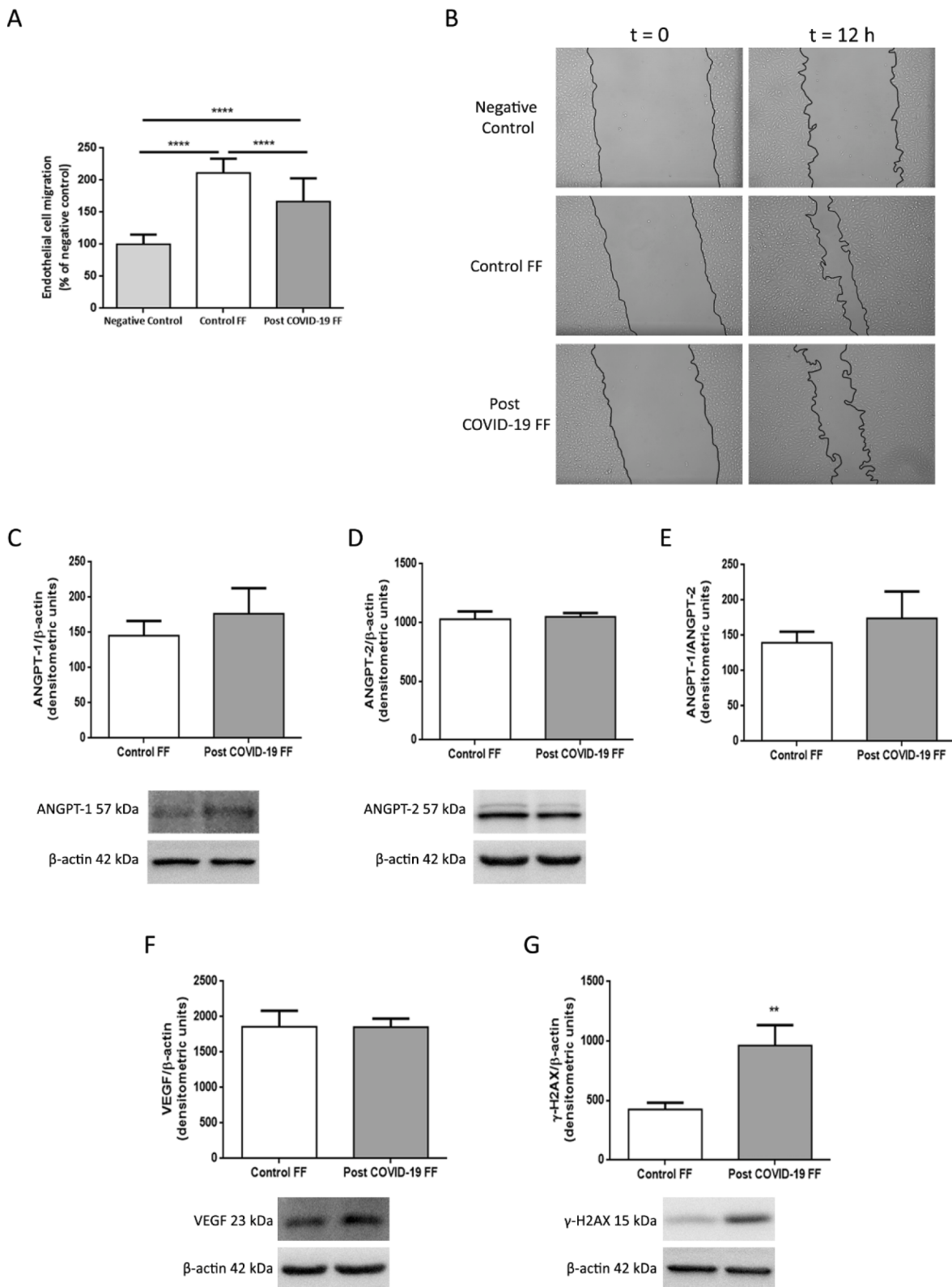


Fig. 4. Effects of FF from recovered COVID-19 patients on endothelial cells. Endothelial migration of EA.hy926 cells stimulated with control or post COVID-19 FF. (A) Quantification of the wound-healing assay. The columns show the percentage of endothelial cell migration normalized to the negative control, which is presented as 100%. Data are expressed as means ± SEM. (B) Representative images taken immediately after wound scratching (t 0) and after 12 h (t 12). Black lines represent the migration fronts. Effects of stimulation with control or post COVID-19 FF on the expression of ANGPT-1 (C); ANGPT-2 (D); ANGPT-1/ANGPT-2 (E); VEGF (F) and γH2AX (G) in EA.hy926 cells. The graphs show the densitometric analysis of protein levels. The density of each band was normalized to the density of the β-actin bands. Lower panels show representative blots for each protein analyzed. * $p < 0.05$.

we showed that FF from post COVID-19 patients decreased StAR and ER β expression in human non-luteinized granulosa cells compared with those stimulated with control FF. Dang et al. (2017) have previously shown that cytokines such as IL-1 β induce the expression of StAR and stimulate steroid synthesis in human granulosa-lutein cells (54). Taken together, these data suggest that low IL-1 β levels detected in FF from post COVID-19 patients could be partially responsible for the decreased StAR expression and alter the steroid synthesis in granulosa cells, thus affecting oocyte development and maturation.

As described above, VEGF is the main angiogenic factor involved in the formation of microvasculature within ovarian follicles (55). Other angiogenic factors, such as angiopoietins, are required for the maturation of newly formed blood vessels. Previously, we showed in a rat model that inhibition of VEGF and ANGPT-1 causes an imbalance in the ratio of antiapoptotic: proapoptotic proteins that leads more follicles to atresia (56,57). In the present study, stimulation with FF from post COVID-19 patients resulted in a significant decrease in endothelial cell migration compared with that of control FF. This finding is consistent with the decrease in VEGF concentration that we observed in post COVID-19 FF. Indeed, altered endothelial migration could be a direct consequence of low VEGF concentrations since this affects new blood vessel formation.

Conversely, several studies, including ours, have demonstrated the cytoprotective effect of VEGF in the bovine and rat ovary (56,58). Here, we showed that FF from post COVID-19 patients significantly decreased the expression of VEGF in non-luteinized human granulosa cells. Even though the presence of post-COVID-19 FF did not seem to influence granulosa cell proliferation compared with that of control FF, our results indicate that decreased VEGF levels might affect follicular cell function and, consequently, damage oocytes.

Double-strand breaks (DSBs) affect the stability of the genome and represent one of the most critical lesions for cell survival (59). γ H2AX is a well-known marker for the detection of chromatin modifications linked to DNA damage and is used to assess various cellular processes such as aging, cancer, and inflammation (60–62). In particular, γ H2AX is utilized to predict chronic inflammatory conditions that precede cancer as well as cardiovascular and nervous system disorders. Moreover, the influx of viral antigens can cause an inflammatory response, making γ H2AX a potential marker of viral infection. For instance, Nichols et al. (2009) observed that increased γ H2AX levels were induced by replicating viral proteins during adenovirus infection (63). In our study, we demonstrated that FF from recovered COVID-19 patients increased γ H2AX levels compared with FF from control patients in both endothelial and granulosa cells. Therefore, a possible explanation for this is that systemic and/or local infection of SARS-CoV-2 may promote the entry of lymphocytes and macrophages to the ovary. This would affect the synthesis of pro- and anti-inflammatory cytokines that regulate the release of reactive oxygen species, possibly leading to disruption of the DNA integrity of follicular and endothelial cells.

In conclusion, the results described for the first time in this study evidence that infection with SARS-CoV-2 could damage ovarian function, alter the follicular microenvironment and potentially affect reproductive outcomes. Our results indicate that this viral infection leads to the presence of IgG antibodies against SARS-CoV-2 in FF, in addition to decreased VEGF and IL-1 β levels in FF. We also found a negative relationship between SARS-CoV-2 IgG levels in FF and the numbers of retrieved and mature oocytes from the same patients, further corroborating that COVID-19 might jeopardize reproductive outcomes. Additionally, post COVID-19 FF alters steroidogenic parameters and VEGF expression in granulosa cells as well as impair migration in endothelial cells. Moreover, these FF severely damage DNA stability and integrity in both granulosa and endothelial cells. Further research on SARS-CoV-2 infection and its impact on ovarian microvasculature and folliculogenesis is of the essence. In particular, elucidating which FF components in the ovarian microenvironment have a negative impact on oocytes should be examined more closely.

One of the limitations of our study is that the enrolled patients were analyzed 3 to 9 months after SARS-CoV-2 infection. Therefore, more studies are needed to evaluate whether these ovarian alterations can be reverted after longer periods of time, which would allow physicians to design an optimal fertility protocol for patients recovered from COVID-19 and to prevent potential complications during the ART treatments due to a recent SARS-CoV-2 infection. Studies with a larger population size could provide more definite evidence on the reproductive performance of recovered COVID-19 female patients.

5. Conclusion

Greater efforts are needed to ensure that COVID-19 is taken into account as a relevant factor influencing female reproduction and to use this information to further improve clinical interventions and public health policies. Finally, our study provides a solid groundwork for future research to continue evaluating the potential effects of SARS-CoV-2 infection on ovarian function and its implications on women's fertility.

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CRediT authorship contribution statement

Yamila Herrero: Investigation, Conceptualization, Formal analysis, Data curation, Validation, Visualization, Writing – review & editing. **Natalia Pascuali:** Investigation, Data curation, Writing – review & editing. **Candela Velázquez:** Investigation, Data curation. **Gonzalo Oubiña:** Investigation, Data curation. **Vanesa Hauk:** Investigation, Data curation.

Ignacio de Zúñiga: Collection of clinical samples. **Mariana Gómez Peña:** Collection of clinical samples. **Gustavo Martínez:** Collection of clinical samples. **Mariano Lavolpe:** Collection of clinical samples. **Florencia Veiga:** Collection of clinical samples. **Fernando Neuspiller:** Collection of clinical samples. **Dalhia Abramovich:** Writing – review & editing. **Leopoldina Scotti:** Investigation, Data curation, Writing – review & editing. **Fernanda Parborell:** Conceptualization, Supervision, Formal analysis, Data curation, Validation, Visualization, Writing – original draft, Writing – review & editing, Funding acquisition, Project administration.

All authors approved the final version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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