The Parity-Associated Microenvironmental Niche in the Omental Fat Band Is Refractory to Ovarian Cancer Metastasis

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Abstract

Ovarian cancer is an insidious and aggressive disease of older women, typically undiscovered before peritoneal metastasis due to its asymptomatic nature and lack of early detection tools. Epidemiologic studies suggest that child-bearing (parity) is associated with decreased ovarian cancer risk, although the molecular mechanisms responsible for this phenomenon have not been delineated. Ovarian cancer preferentially metastasizes to the omental fat band (OFB), a secondary lymphoid organ that aids in filtration of the peritoneal serous fluid (PSF) and helps combat peritoneal infections. In the present study, we assessed how parity and age impact the immune compositional profile in the OFB of mice, both in the homeostatic state and as a consequence of peritoneal implantation of ovarian cancer. Using fluorescence-activated cell sorting analysis and quantitative real-time PCR, we found that parity was associated with a significant reduction in omental monocytic subsets and B1-B lymphocytes, correlating with reduced homeostatic expression levels of key chemoattractants and polarization factors (Ccl1, Ccl2, Arg1, and Cxcl13). Of note, parous animals exhibited significantly reduced tumor burden following intraperitoneal implantation compared with nulliparous animals. This was associated with a reduction in tumor-associated neutrophils and macrophages, as well as in the expression levels of their chemoattractants (Cxcl1 and Cxcl5) in the OFB and PSF. These findings define a preexisting "parity-associated microenvironmental niche" in the OFB that is refractory to metastatic tumor seeding and outgrowth. Future studies designed to manipulate this niche may provide a novel means to mitigate peritoneal dissemination of ovarian cancer.

Introduction

Ovarian cancer is responsible for 140,000 deaths a year in women worldwide (1) with one of the highest incidence-to-death ratios in the United States due to late detection, tumor heterogeneity, and a high rate of metastasis (2). However, epidemiologic studies indicate that among other factors, parity (child-bearing) may provide protection against the development of ovarian cancer (3). Nonetheless, little is known about the persistent molecular and cellular changes that modulate ovarian cancer development as a result of child-bearing.

As a largely asymptomatic disease in the early stages, ovarian cancer is rarely detected before metastasis. During metastasis, ovarian cancer cells exfoliate from the primary tumor, disseminate throughout the peritoneal cavity in the serous fluid, and preferentially seed in the omental fat band (OFB; ref. 4). As the primary metastatic site, it is typically removed during surgical tumor debulking to slow disease progression. The OFB is considered a secondary lymphoid organ, contributing to immunosurveillance in the peritoneal cavity and its removal results in impaired antibacterial responses in the abdomen and increased risk of subsequent infections (5). It is composed of fatty tissue interspersed with immune cell aggregates or "milky spots" (6), consisting of leukocytes, stem and progenitor cells, fibroblasts and endothelial cells (7) collectively referred to as the stromal vascular fraction (SVF). Disseminated tumor cells adhere to milky spots within hours (8), promoting a protumorigenic microenvironment that supports subsequent tumor outgrowth (6, 8, 9). However, the complex and dynamic interactions between metastatic cancer cells and leukocytes within the OFB have not been well characterized.

We have shown previously that the homeostatic immune microenvironment of the OFB significantly differs from that of other intraperitoneal fat depots with a distinct leukocyte profile, and a robust cytokine signaling network (10). It is unknown how this immune microenvironment is impacted by aging or parity, which may have critical implications for the generation of a metastatic niche that determines successful tumor adherence and outgrowth. However, epidemiologic studies have reported increased ovarian cancer incidence in older women but a protective effect associated
with parity (11). Here, we postulated that parity may induce changes in the OFB that result in a preexisting immune microenvironment that is protective against cancer metastasis. As child-bearing is inherently associated with an older demographic, we chose three sets of female mice to distinguish between age- and parity-specific changes: 5-month-old nulliparous young adults, 11-month-old nulliparous mature adults, and 12-month-old mature parous adults. Given its importance as a primary metastatic site, in the present study, we comparatively characterized the SVF and gene expression profiles of the OFB as a function of age and parity.

Materials and Methods

Cell lines

The mouse ovarian surface epithelial (MOSE) cell model used in this study was developed from C57BL/6 mice and characterized previously (12). Tumorigenic MOSE cells were passaged once in vivo by intraperitoneal injection into C57BL/6 mice and recollected via peritoneal lavage following a 4- to 6-week incubation period to select for a more aggressive phenotype. These MOSE cell variants (MOSE-LFFLv) were subsequently transduced with firefly luciferase (Fl) lentiviral particles (GeneCopoeia) as described previously (13) to facilitate live in vivo imaging of cancer cell outgrowth. The characteristics of MOSE-LFFLv will be reported elsewhere. MOSE-LFFLv cells were routinely maintained in high glucose Dulbecco’s modified Eagle medium (DMEM; Invitrogen), supplemented with 4% FBS (Hyclone), 100 mg/mL penicillin and streptomycin, and 4 μg/mL puromycin (lentiviral particles use a puromycin resistance marker for selection of transduced cells).

Animals

Female C57Bl/6 mice (Harlan Laboratories) were housed 5 per cage in a controlled environment (12 hour light/dark cycle at 21°C with free access to water and food (18% protein rodent chow, Teklad Diets). Young adult nulliparous mice (5 months of age, 21 g average body weight), mature adult nulliparous mice (11 months of age, 30 g average body weight), and mature parous mice (12 months of age, 31 g average body weight) were sacrificed by CO2 asphyxiation. Mouse studies were carried out in accordance with the guidelines approved by the Virginia Tech Institutional Animal Care and Usage Committee.

MOSE-LFFLv injection

Young adult nulliparous and mature parous mice (n = 10 per group) were injected intraperitoneally with either 1 × 10⁴ MOSE-LFFLv cells in 300 μl sterile calcium- and magnesium-deficient PBS, or mock-injected (PBS alone) and sacrificed at 21 days postinjection.

Peritoneal cancer index

To quantify relative tumor burden at the time of sacrifice, the peritoneal cancer index (PCI) was determined as described previously (14, 15), with minor modifications. The original PCI was adapted to apply to tumor size and region in mice; “quadrant areas” were modified to represent distinct organs and their mesentery to evaluate preferential seeding sites. Specific regions evaluated included peritoneal cavity lining, ovaries, lesser omentum, greater omentum (OFB), diaphragm, liver, stomach, pancreas, spleen, kidney, small intestine, small intestine mesentery, large intestine, and large intestine mesentery. Tumor size was scored as (0), no visible tumor; (1), <1 mm; (2), 1–3 mm; or (3): >3 mm or solid mass. The maximum PCI score was 42, reflecting maximal lesion size in each of the 14 designated areas. Relative PCI scores were further validated by quantitative real-time PCR (qRT-PCR) analysis of FFL gene expression used as a tumor cell reporter gene.

Tissue and peritoneal serous fluid harvest

The OFB was harvested from each mouse post mortem, weighed, rinsed with PBS alone, and processed for fluorescence-activated cell sorting (FACS) analysis or placed into RNA later (Qiagen) and stored at −80°C. Resident peritoneal cavity cells were collected via peritoneal lavage with 5 ml of 1 mmol/L EDTA in PBS and stored at −80°C. The effluent was centrifuged, subjected to erythrocyte lysis (155 mmol/L NaH4Cl, 10 mmol/L KHCO3, and 0.1 mmol/L EDTA), and further processed as described below.

Tissue digest

SVFs were isolated by digesting individual OFBs (n = 4–6) in GKN buffer (8.00 g/L NaCl, 0.40 g/L KCl, 3.56 g/L Na2HPO4·12H2O, 0.78 g/L NaH2PO4·2H2O, and 2 g/L D (+) glucose, pH 7.4) containing 1.8 mg/ml type IV collagenase, 10% FBS, and 0.1 mg/ml DNase as previously described (10). Following digest at 37°C for 45 minutes, cells were passed through a 40-μm cell strainer, and erythrocytes were lysed (see above).

FACS analysis

Single-cell suspensions derived from OFB and peritoneal serous fluid (PSF) were washed in flow buffer (2% BSA in PBS without calcium or magnesium), blocked with Fc block (BD Biosciences) for 10 minutes at 4°C, rinsed and incubated with fluorochrome-labeled antibody combinations (available upon request) for 20 minutes at 4°C. Antibodies specific for mouse CD45, CD11b, CD11c, F4/80, Ly6C, CD4, CD44, CD62L, B220, CD19, NK1.1, and Ly6G were obtained from eBioscience. CD3 and CD8 antibodies were obtained from BD Biosciences. Before analysis, cells were washed twice and resuspended in PBS with propidium iodide for dead cell exclusion. FACS analysis was conducted on a FACS Aria (BD Biosciences) and data were analyzed using FlowJo (TreeStar) software.

Quantitative real-time PCR

Individual OFBs were homogenized in Qiazol (Qiagen) and RNA was purified using the RNeasy Lipid Tissue Kit (Qiagen), according to the manufacturer’s instructions. RNA concentration was determined using a NanoDrop1000 spectrophotometer. RNA (n = 4–6) was subjected to the iScript cDNA synthesis system (Bio-Rad) according to the manufacturer’s protocol. qRT-PCR was conducted with 12.5 ng...
cDNA per sample using gene-specific SYBR Green primers (primer sequences are available upon request) designed with Beacon Design software. SensiMix SYBR and Fluorescein mastermix (Bioline) was used in a 15 μL reaction volume. qRT-PCR was conducted for 42 cycles at 95°C for 15 seconds, 60°C for 15 seconds, and 72°C for 15 seconds, preceded by a 10-minute incubation at 95°C on the iQ5 (Bio-Rad). Melt curves were generated to ensure fidelity of the PCR product. The housekeeping gene was L19 (10) and the ΔΔCt method (16) was used to determine fold differences.

Statistical analysis
Data were expressed as mean ± SEM. FACS analysis and qRT-PCR data were analyzed using a one-way ANOVA coupled with a Tukey post hoc test in SigmaPlot (Systat Software). Differences were considered statistically significant at P < 0.05.

Results

OFB size and cellularity
The size of the OFB increased significantly with age between 5- and 11-month-old nulliparous mice, coinciding with overall age-associated weight gain of the animals (14.4 ± 1.5 g and 28.2 ± 2.2 g; P < 0.01). Parity was associated with an additional increase in OFB weight (Fig. 1A; P < 0.01), although the average body weight of these age-matched groups were not significantly different (29.8 ± 0.8 g vs. 31.7 ± 0.7 g). The OFB SVF cell count was significantly elevated as a function of both age and parity, increasing 800% in parous mice (Fig. 1B; P < 0.01). Therefore, parity induced a change in stromal vascular cell influx or proliferation and not just an increase in overall OFB adiposity. The proportion of CD45+ leukocytes represented approximately 50% of the SVF in both sets of nulliparous mice but more than 95% of the SVF in parous mice (Fig. 1C; P < 0.01). To further define the age- and parity-associated signature, we evaluated expression of a set of immune-related genes using qRT-PCR on whole tissue samples. As shown in Fig. 1D, there were both age- and parity-associated differences in the expression of a number of important cytokines and chemokines in the homeostatic state. Notably, in mature nulliparous animals, the expression of chemotactic molecules for monocytes (Ccl1, Ccl4, and Ccl7; P < 0.05) as compared with young nulliparous mice was increased. Expression of Tgf-b, an important regulator of tumor cell invasion and metastasis, was significantly higher in older mice, irrespective of parity (P < 0.01). Parity-specific changes included a significantly lower expression of neutrophil chemoattractants (Cxcl1 and Cxcl2; P < 0.05) and alternative activation-related genes characteristic of tumor-associated macrophages (Arg1 and M6pr; P < 0.05). Thus, inherent changes that occur as a result of aging and child-bearing can affect the signaling milieu in the OFB.

OFB SVF characterization
The OFB SVF was further characterized via FACS analysis to identify age- and parity-specific differences in immune cell composition. Viable cells (propidium iodide exclusion) were separated into CD45+ leukocytes and CD45- stromal...
constituents. CD45^+ cells were subsequently separated into R1 (lymphocyte) and R2 (monocyte/granulocyte) gates based on forward/side scatter (Fig. 2A), and leukocyte subsets were identified on the basis of well-defined surface markers. The CD45^+ subsets associated with the OFB in nulliparous mice were comparable, irrespective of age. However, the immune cell composition of the parous OFB was strikingly different, supporting the hypothesis that parity leads to establishment of a unique protective microenvironment. In the OFB of nulliparous mice, the lymphocyte to monocyte/granulocyte (R1:R2) ratios were approximately 6:4 independent of age, whereas lymphocytes represented almost 90% of the leukocytes isolated from the parous OFB (Fig. 2B). This was mirrored in the PSF, denoted by a 20% increase in the proportion of lymphocytes to monocytes/granulocytes in parous mice as compared with mature nulliparous mice (P < 0.05; Supplementary Table S1).

The parity-associated increase in lymphocytes was reflected across numerous subsets including CD3^+ T cells (P < 0.01), CD19^+ B cells (P < 0.05), and CD11c^+ dendritic cells (P < 0.01) with concomitant decreases in F480^+ macrophages (P < 0.01) and NK1.1^+ natural killer (NK) cells (P < 0.01) compared with nulliparous mice (Fig. 2C). Compared with their nulliparous counterparts, the parous OFB also displayed significantly increased CD3^-CD4^- T cells, and significantly decreased CD3^-CD8^- Tc, and CD3^+CD4^-CD8^- cells (P < 0.05; Fig. 2D). Parity also induced a significant increase in the proportion of T cells and B cells in the PSF (P < 0.05; Supplementary Table S1), although levels of NK cells and dendritic cells were unchanged. Notably, there was a significant parity-associated shift in the subsets of B cells residing in the OFB. CD11b^+ B220^b/c^ B1 cells were the most prevalent subset of B cells in nulliparous mice, whereas in parous mice the CD11b^-B220^-B2-subset was dominant (Fig. 2E). B1 cells are the predominant B-cell type in the peritoneal cavity, and are considered a more "innate-like" population, with receptors for auto-antibodies and conserved bacterial and viral epitopes (17).
This increase in B2-cells could be indicative of a more systematically active humoral B-cell response in parous mice. Parity-associated changes were also evident within OFB macrophage subsets, although these changes were not mirrored in the parous PSF. In the PSF, macrophages are typically subdivided into "large peritoneal macrophages" (LPM), and "small peritoneal macrophages" (SPMs; ref. 18). LPMs can be distinguished via FACS analysis based on forward/side scatter and higher CD11b and F480 surface staining. SPMs increase in the PSF as a result of LPS stimulation and are derived from blood monocytes (18). The applicability of these subsets to the OFB is largely undefined. Here, the PSF contained mostly LPMs in the homeostatic state, with SPMs representing only a minor fraction of the total macrophage population. This trend was not significantly altered by parity (data not shown). In contrast, while the predominant macrophage population in the OFB of nulliparous mice was the CD11b+ F480+ population (SPMs), this population was significantly reduced in parous mice. Furthermore, the CD11b+ F480+ population (LPMs) was virtually undetectable in parous mice, although it represented approximately 8% of the R2 gate in nulliparous mice (Fig. 2F). Collectively, these data suggest that nulliparous mice, irrespective of age, had similar immunomodulatory microenvironments in the peritoneal cavity as denoted by indistinguishable leukocyte profiles at these time points.

**Impact of parity on peritoneal tumor burden**

As parous women have a decreased risk of ovarian cancer, we next evaluated whether the parous microenvironment was more refractory to tumor cell seeding and outgrowth. To investigate this, we used a highly aggressive variant of our MOSE-L cells (MOSE-LFFLv). Implantation of these cells results in rapid and widespread peritoneal outgrowth and ascites in syngeneic C57BL/6 female mice. At 21 days postinjection of 1 x 10^6 MOSE-LFFLv cells, nulliparous and parous mice were euthanized and the PCI was assessed. Young nulliparous mice were chosen for comparison, as only minor changes in gene expression and no notable changes in the immune microenvironments were noted between young and mature nulliparous groups. We reasoned that these comparisons would provide additional insights into mechanistic alterations in the immune microenvironment as a consequence of peritoneal tumor dissemination. Notably, parous mice had a significantly decreased PCI compared with nulliparous mice (Fig. 3A; P < 0.01). To confirm this, we determined relative levels of the FFL reporter gene in the OFB using qRT-PCR. FFL expression, as evidenced by lower ΔCt values (normalized to the housekeeping gene L19), was significantly higher in the OFB of MOSE-LFFLv-injected nulliparous mice than in parous mice (P < 0.05; Fig. 3B). The OFB from PBS-injected mice were negative for FFL reporter gene expression.

Macroscopically, the OFBs in nulliparous mice were devoid of residual adipose tissue and were fully overtaken by fibrous tumor tissue. The average OFB weight increased significantly in cancer-bearing nulliparous mice (Fig. 3C) and 60% of mice developed bloody ascites. In contrast, cancer-bearing parous mice presented with visible individual tumor nodules throughout the OFB, but residual adipose tissue was still highly evident, and no ascites was observed. The OFB weight did not change between MOSE-LFFLv- and vehicle-injected parous mice, confirming a significantly lower OFB tumor burden than in nulliparous mice.

The aggressive growth of MOSE-LFFLv cells in nulliparous animals coincided with a 15-fold increase in the PSF cell count of the OFB (Fig. 3D), although the proportion of CD45^- leukocytes did not change (Fig. 3E). This suggests that the tumor microenvironment induced a proliferation or influx of leukocytes and CD45^- stromal constituents. This trend was not observed in parous mice (Fig. 3D and E), indicating that the OFB microenvironment of parous animals is inherently more resistant to either tumor outgrowth or the recruitment of protumorigenic factors or cell types.

**OBF SVF characterization with ovarian cancer**

The OFB and PSF of ovarian cancer-bearing mice were further characterized via FACS analysis to determine the impact of cancer cell seeding on leukocyte populations. Tumor outgrowth caused a reduction in the proportion of lymphocytes and a concomitant increase in monocyte/granulocytes in the OFB, irrespective of parity (Fig. 4A). This pattern was also evident in the PSF, with an increase in the proportion of monocytes/granulocytes of both nulliparous (19% ± 11.0%; P = 0.21) and parous mice (15% ± 1.6%; P < 0.01; Supplementary Table S2).

Most notably, there was a significant increase in the CD11b^-Ly6C^-Ly6G^- B2-cells in parous mice (15% ± 11.0%; P < 0.01) as a result of cancer cell seeding in the OFB. This population resembles the previously described CD11b^-Ly6C^-Ly6G^- tumor-associated neutrophil (TAN) population (19). In addition, the cancer-associated redistribution of R1:R2 leukocytes in the OFB of nulliparous mice was mirrored across all subsets with decreased CD3^- T cells, CD19^- B cells, and NK1.1^- NK cells, and concomitant increases in F480^- macrophages and CD11c^- dendritic cells. Although levels of Th cells and Tc cells declined with cancer seeding, both double-negative (CD3^-CD4^-CD8^-; DN-T cells) and NK-T cell subsets increased although significance was not quite reached (Fig. 4C). The DN-T cells may represent either an immunosuppressive T-cell population that secretes Tgf-β and Il-10 and directly kills CTLs (20) or γδ T cells (20, 21) albeit neither γδ TCR expression nor intracellular cytokine expression were examined in this study.

No differences in the proportions of B1- and B2-lymphocytes were noted in the OFB of cancer-bearing nulliparous animals (Fig. 4D). However, in the PSF, the B1:B2 ratio increased from 3:1 in the homeostatic state to 5:1 due to MOSE-LFFLv implantation (P < 0.05; data not shown). As B1 cells act as the bridge between innate and adaptive immunity, producing low-affinity antibodies, this may be reflective of an ineffective humoral immune response similar to human patients that present with antitumor antibodies that afford no disease protection (22). It is important to note that while the proportion of B1:B2 cells increased with cancer, the overall percentage of both B1- and B2-cells in...
the PSF leukocyte population actually decreased as a result of shifting R1:R2 ratios. Furthermore, the CD11blo/F480- monocyte subset levels significantly decreased as a result of cancer (Fig. 4E). Therefore, the cancer-associated OFB immune profile in nulliparous mice included increased proportions of TANs and macrophages and decreased lymphocyte and monocyte populations.

To complement our FACS analysis, we used qRT-PCR to characterize the overall signaling milieu of the OFB microenvironment after peritoneal cancer dissemination. Expression patterns represent the tissue as a whole, and thus are reflective of adipocytes, the SVF, and cancer cells within the tissue. A panel of cytokines and chemokines was used to provide an overview of genes that may contribute to a protumorigenic microenvironment (Supplementary Tables S3 and S4). The expression of B-cell chemoaffectants (Cxc13 and Il-5) was significantly lower, whereas monocyte-associated cytokines (Ccl2, Ccl20, inos, Arg1, and Ym1) and neutrophil chemoattractants (Cxc1, Cxc3, Cxc5, and Cxc3) were significantly higher in nulliparous mice after cancer seeding (Fig. 4F). These changes in the microenvironmental transcriptome support the cellular changes found in the SVF, namely the decrease in B cells and approximately 100-fold increase in TANs in the OFB of cancer-bearing nulliparous mice.

In contrast to nulliparous animals, there was no significant net gain of leukocytes in the OFB of parous animals after tumor outgrowth (see Fig. 3D and E). However, a similar cancer-associated shift in the leukocyte subsets was detected, denoted by a decline in T and B cells and an increase in macrophages and TANs (Fig. 5A). Among CD3+ leukocytes (Fig. 5B), only an increase in the CD4-/C0, CD8-/C0 double-negative subset was noted as a consequence of tumor outgrowth. The influx of the TANs was significantly reduced, representing only 7% of the CD45+ population in parous mice, as opposed to the 25% in nulliparous animals (see also Fig. 4B). This suggests that cancer-mediated recruitment of TANs to the OFB may be compromised or dampened as a consequence of parity. It should also be noted that all lymphocyte subsets were maintained at high levels in the OFB of parous animals, irrespective of cancer, which may help to maintain an activated state that is less conducive to...
cancer cell proliferation. This is further supported by the B-cell subset distribution shift toward the B2 phenotype in parous animals (Fig. 5C), which contrasts that observed in nulliparous animals (Fig. 4D). Unlike nulliparous mice, there was no significant cancer-associated decline in CD11b^{hi}/F480^- monocytes in parous mice (Fig. 5D). However, these levels were already significantly elevated in the homeostatic parous OFB.

TANs in the parous PSF were elevated as a result of cancer (P < 0.01; Supplementary Table S2), albeit at a lower level than in nulliparous mice. In addition, the PSF in parous animals displayed a loss of LPMs and an increase in SPMs after MOSE-LFFLv disseminaton. The recruitment of SPMs is indicative of an innate-like inflammatory response, thus parous animals may be able to override, at least transiently, the inherent immnosuppressive program elicited by the MOSE-LFFLv cells.

Comparative assessment of the gene expression profile of the parous OFB revealed that the expression of neutrophil chemoattractants was significantly higher in cancer-bearing mice (Cxc11, Cxc12, Cxc13, and Cxc15; Fig. 5E). This correlates with the recruitment of TANs following cancer cell seeding, highlighting the importance of TANs in the propagation of the protumorigenic microenvironment. Together, our data suggest that the preexisting parity-associated microenvironment within the peritoneal cavity is inherently more resistant to tumor cell seeding and outgrowth by virtue of its ability to modulate recruitment of protumorigenic immune cell types, either before tumor cell attachment (premetastatic niche) or following seeding and outgrowth.

Discussion

Epidemiologic studies indicate that parity reduces the risk of both ovarian and breast cancer development. Although...
the molecular mechanisms of decreased ovarian cancer occurrence remain unclear, breast cancer studies suggest that protective effects relate to decreased cancer metastasis (3). It is possible that child-bearing results in a naturally occurring protective state that could be harnessed and used in the treatment of ovarian cancer, preventing fatal
metastatic outgrowth. Our results show that parity, but not age, altered the OFB immune profile in the homeostatic state. This parity-associated immune profile was positively correlated with reduced peritoneal tumor burden. A more comprehensive understanding of the dynamic cellular interactions during metastatic outgrowth is critical for the development of treatment strategies to effectively target the tumor microenvironment at the time of disease discovery. These insights may ultimately lead to novel strategies to repolarize the immune microenvironment of the OFB in a manner that reflects a microenvironment refractory to cancer growth.

Here, we compared the immune profile of the OFB as a function of age and parity to assess whether a preexisting microenvironment exists that may be refractory to tumor growth. To this end, we characterized the leukocyte composition and cytokine expression profiles of the OFB and PSF, both in the homeostatic state and after aggressive ovarian cancer cell implantation. In the homeostatic state, parity (but not age) resulted in a marked decrease in monocytic cell subsets and affiliated chemoattractants, and a shift to predominantly B2-, as opposed to B1 B lymphocytes. Following syngeneic cancer cell implantation, parous mice exhibited a significantly reduced tumor burden as compared with nulliparous mice. The tumor microenvironment was denoted by higher TANs and TAMs, and an increase in B1 cells in nulliparous animals, a trend that was dampened in parous mice in conjunction with decreased tumor growth. Thus, we postulate that the parous OFB compositional profile is indicative of a preexisting niche that is partially refractory to metastasis.

To more fully elucidate an expression signature indicative of an inherently protective immune microenvironment in the parous state, we evaluated a panel of immunoregulatory cytokines and chemokines. Figure 6 summarizes all statistically significant gene expression changes associated with age, parity, cancer metastasis, or any combination therein ($P < 0.05$; see Supplementary Tables S3 and S4 for full list of

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Figure 6. Gene expression signatures in the OFB associated with age, parity, or cancer cell seeding and outgrowth. Venn diagram representing significantly altered genes $*, P < 0.05$, and genes trending toward significance $P = 0.05–0.08$. White boxes indicate increased expression, gray boxes indicate decreased expression.
Impairing T-cell priming. Hence, B lymphocyte subsets protectively immune responses against tumors (37) by characterized by TGF-β instead of malignant cells (36). Regulatory B cells, characterized by Arg1 and M6pr; P < 0.05). This correlates with the observed reduction of these cell types in the parous OFB, and may represent a metastasis-resistant microenvironmental signature. The most conspicuous cancer-related finding was the significant increase in neutrophil chemotactants (CCL3, CCL11, -2, -3, and -5). Cancer-bearing groups also exhibited increased Arg1 expression, and young adult nulliparous mice had increased Ym1 expression, indicative of the presence of TAMs.

Given the protumorigenic nature of TAMs (23, 24), TANs (25, 26), and myeloid-derived suppressor cells (27, 28), the cancer-related increase in these cell types was expected. Therefore, the dampened influx of these subsets in parous mice may partially define the preexisting protective niche in the OFB. In other words, parity leads to a reduction in the levels of cell subsets targeted for protumorigenic polarization. A microenvironment that lacks these subsets, or is partially refractory to cancer-associated recruitment may slow the dynamics of tumor seeding and growth, resulting in delayed disease development.

The parous OFB also contained a greater proportion of both T- and B lymphocytes. Tumor-infiltrating lymphocytes (TIL) correlate with improved prognosis and survival in a variety of murine and human cancer models (29–31). Therefore, a net gain in lymphocytes may be another attribute of the protective parity signature in the OFB. Although the effects of increased T-cell populations in the tumor microenvironment have been well defined, less information is available describing tumor-infiltrating B cells (TIL-B) and their impact on cancer progression (32). The presence of CD20+ B cells together with CD8+ T cells in the tumor microenvironment has been attributed to higher survival rates than the occurrence of either cell type alone, indicating a protective cellular signature (33). Interestingly, TIL-Bs produce granzyme B upon interleukin (IL)-21 stimulation, which would be cytotoxic to tumors; upon IFN-α or Toll-like receptor (TLR) agonist stimulation, they can directly kill tumor cells via TRAIL signaling (34, 35), also supportive of their antitumorigenic potential. In contrast, killer B cells produce apoptotic death-inducing ligands including Fas ligand (FasL), TRAIL, and programmed death ligands 1 and 2 (PD-L1 and PD-L2; ref. 36). However, their presence in the tumor microenvironment actually inhibits protective immune responses, inducing apoptosis of cytolytic effector cells instead of malignant cells (36). Regulatory B cells, characterized by TGF-β and IL-10, also dampen and inhibit protective immune responses against tumors (37) by impairing T-cell priming. Hence, B lymphocyte subsets are gaining widespread acceptance as key regulators and modulators of both pro- and antitumorigenic responses.

In this study, there was a shift in the B-cell distribution of B1 and B2 cells as a consequence of parity, with B2 cells increasing significantly in the parous OFB. B1 cells play an important role in immunosurveillance in the peritoneal cavity, and are in a constant flux between the PSF and the OFB. During infection, B1 cells generate large amounts of low-affinity immunoglobulin M (IgM), immunoglobulin A (IgA), and immunoglobulin G3 (IgG3), ensuring early protection (38). B1 cells have been described as the precursors of tumor-promoting regulatory B cells (Breg; ref. 39). B1 cells also possess many of the above-mentioned regulatory properties, including constitutive FasL and PD-L2 expression and the ability to produce IL-10. Although the B2 subset is predominant in the parous OFB in the homeostatic state, with cancer cell seeding, the proportion of B1:B2 cells increases slightly in both parous and nulliparous mice. Collectively, this information may support the theory that B1 cells are subject to repolarization toward Bregs in the presence of cancer. Alternatively, the parity associated omental B2 cells may represent a subset such as the aforementioned killer B cells that exhibit antitumorigenic activity. Future studies defining which B-cell subsets in parous animals are actually antitumorigenic will help clarify this question.

Parity was indeed associated with a significant reduction in tumor burden following syngeneic ovarian cancer cell implantation in the peritoneal cavity. The most significant cancer-associated finding was the increase in the proportion of TANs in the OFB. Hence, the ability to modulate early TAN infiltration may represent another protective element of the parous OFB. TANs are a significant portion of the inflammatory infiltrate in a variety of tumor microenvironments and numerous cancer cell lines express neutrophil chemotactants, highlighting their importance in supporting the tumor milieu (40–43). Although depletion of TANs limits tumor metastasis, neutrophil accumulation in tumors is correlated with poor prognosis in clinical settings (41, 44, 45). The presence of TGF-β in the tumor microenvironment is the driving factor in the polarization of neutrophils to a protumorigenic (or "N2") type (46). We found that Tgf-β expression was increased 100-fold in the OFB in both older nulliparous and parous animals. This age-related increase may play a crucial role in the increased ovarian cancer incidence in postmenopausal women. The decreased tumor burden observed in parous mice may be a result of decreased protumorigenic subsets and chemotactant expression (e.g., TANs and CCL1, -2) immediately available within the OFB, despite increased Tgf-β expression.

Parity also resulted in an almost complete loss of CD45+ progenitor populations present within the OFB. An important component in the tumor cellular milieu is the stromal contingent. These cells are recruited from adipose tissue and bone marrow to provide crucial growth factors, matrices, cytokines, and nutrients to support rapid tumor growth (47, 48). The loss of progenitor cells in the OFB may reflect another aspect of the "protective signature" associated with...
child-bearing, in that the scaffolding or accessory cells crucial to rapid tumor growth are not initially available in situ. This may indicate a parity-associated differentiation or egress of CD45− progenitor populations within the OFB, in agreement with an increase in differentiation signals previously reported as part of a “parity signature” in mammary tissue (3).

The OFB is not only important as a preferential site for ovarian cancer, but also because of its role in peritoneal immunosurveillance. Its removal results in subsequent impaired antibacterial responses in the abdomen, and an increased chance of sepsis following surgery (5). Clearly, removal of this vital organ is not ideal, but it is generally regarded as necessary to help minimize recurrent disease. Our study suggests that a more comprehensive analysis of the parity-induced molecular and cellular changes within this immunologically and metastatically relevant microenvironment is needed in humans. Confirmation of a protective “parity-associated signature” in humans could help in the design of novel immunotherapies that induce or establish this inherent protective state (3).

In conclusion, our data support epidemiologic findings suggesting that child-bearing provides inherent partial protection against ovarian cancer (11, 49, 50). It is worth noting that the parity-associated protective microenvironment in the peritoneal cavity is only transient and eventually the outgrowth of cancer cells shifts the balance back toward a protumorigenic state. Understanding what defines the transient nature of this refractory state may provide novel insights to modulate the OFB and prevent recurrent disease. Although our studies do not address whether parity mitigates early stages of ovarian tumorigenesis, they do highlight a protective effect against peritoneal seeding and outgrowth. Future studies are clearly warranted to understand how the OFB could be repolarized toward a parity-associated protective state in high-risk patients, or modulated to help delay or prevent recurrent disease in patients with advanced-stage ovarian cancer.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Authors’ Contributions

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The Parity-Associated Microenvironmental Niche in the Omental Fat Band Is Refractory to Ovarian Cancer Metastasis


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