Multiple Roles of Perforin in Hampering ERBB-2 (Her-2/neu) Carcinogenesis in Transgenic Male Mice

Marco Macagno, Silvio Bandini, Lorenzo Stramucci, Elena Quaglino, Laura Conti, Elisa Balmas, Mark J. Smyth, Pier-Luigi Lollini, Piero Musiani, Guido Forni, Manuela Iezzi and Federica Cavallo

J Immunol 2014; 192:5434-5441; Prepublished online 30 April 2014;
doi: 10.4049/jimmunol.1301248
http://www.jimmunol.org/content/192/11/5434

Supplementary Material
http://www.jimmunol.org/content/suppl/2014/04/30/jimmunol.1301248.DCSupplemental

References
This article cites 31 articles, 12 of which you can access for free at:
http://www.jimmunol.org/content/192/11/5434.full#ref-list-1

Subscription
Information about subscribing to The Journal of Immunology is online at:
http://jimmunol.org/subscription

Permissions
Submit copyright permission requests at:
http://www.aai.org/About/Publications/JI/copyright.html

Email Alerts
Receive free email-alerts when new articles cite this article. Sign up at:
http://jimmunol.org/alerts
Multiple Roles of Perforin in Hampering ERBB-2 (Her-2/neu) Carcinogenesis in Transgenic Male Mice

Marco Macagno,* Silvio Bandini,* Lorenzo Stramucci,† Elena Quaglino,* Laura Conti,* Elisa Balmas,* Mark J. Smyth,‡,§ Pier-Luigi Lollini,∥ Piero Musiani,† Guido Forni,* Manuela Iezzi,†,‡ and Federica Cavallo*‡,¶

Perforin (pfp)-mediated cytotoxicity is one of the principal immunosurveillance mechanisms involved in the fight against cancer. However, its importance in spontaneous epithelial cancer is still poorly defined. In this study, we use a realistic mouse model that displays many features that are equivalent to human pathology to evaluate the role of pfp-dependent immunosurveillance by comparing tumor progression in rat ERBB-2 (neu) transgenic, pfp-proficient (neu+/pfp+) or pfp-deficient (neu+/pfp−) BALB/c male mice. Adult neu+/pfp+ males developed poorly differentiated salivary carcinomas, whereas neu+/pfp− males displayed their salivary carcinomas noticeably earlier and showed zones of more highly differentiated tumor, indicating that pfp-mediated immunosurveillance is able not only to delay the growth kinetic of an aggressive epithelial tumor, but also to shape its histology. The role of pfp-mediated immunosurveillance appeared to be of even more dramatic importance against the less aggressive male mammary carcinomas. In neu+/pfp+ males, the incidence of mammary carcinomas was a sporadic and late event. In contrast, in neu+/pfp− males their incidence was four-fold higher. This higher cancer incidence was associated with a 2-fold higher occurrence of persisting mammary remnants, a major risk factor for mammary cancer in male mice, and one that would appear to be due to pfp’s previously unidentified involvement in male mammary gland rejection during embryogenesis. This work thus provides further proof of the complex role that the immune system plays in the body and gives new insight into the pathogenesis of epithelial tumors, demonstrating that the penetrance and malignancy of a tumor may be dramatically affected by pfp-dependent mechanisms. The Journal of Immunology, 2014, 192: 5434–5441.

Observational studies linked to clinical outcome analysis in cancer patients that have been carried out in recent years have displayed the prognostic and predictive value of the tumor microenvironment inflammatory state. This has generated a new wave of interest in the immunosurveillance phenomenon (1). Natural immune surveillance against the onset of cancer is one of the most important tenets in experimental tumor immunology (2, 3). Extensive evidence has shown that immunodeficient mice develop more carcinogen-induced and spontaneous cancers than do wild-type mice, and that tumor cells from immunodeficient mice are more immunogenic than those from immunocompetent mice (4). Numerous studies have elucidated several molecular (5) and cellular (6, 7) immune surveillance mechanisms that hamper tumor onset and shape its growth. However, because their role in spontaneous epithelial cancer is poorly defined, the importance of immunosurveillance in the control of most common human cancers is still difficult to grasp.

Alterations in the ERBB-2 oncogene and its signal transduction pathways are among the causes of epithelial cell neoplastic transformation, carcinoma progression, metastatic spreading, and resistance to therapy (8). In human pathology, ERBB-2 (Her-2) overexpression and mutations are evident in 30–40% of epithelial tumors and are associated with the early onset of precancerous lesions, increased metastasis, and severe prognoses (9). In human breast cancer, gene amplification and protein overexpression of ERBB-2 are associated with poor prognosis (10). Similarly, high-grade human salivary gland carcinomas harbor increased ERBB-2 protein expression and gene copy number (11).

In rats, a single point mutation in the transmembrane domain favors ERBB-2 homo- and heterodimerization and transforms the rat proto-oncogene into a dominant oncogene (neu) (12). In a neu transgenic BALB/c (BALB/neuT) mouse strain, females develop fast-growing mammary carcinomas in all their mammary glands (13). However, mammary neu* carcinomas in BALB/neuT males are late sporadic events, and the prominent cause of death is multifocal poorly differentiated acinic adenocarcinoma that initially involves the parotid and then the submandibular glands (14). At 4 wk of age, males display multiple foci of atypical salivary gland hyperplasia, at the duct and acinic level, that progress to become poorly differentiated carcinomas that are clinically evident at the week 26 of age (14).
The consistent genetic predisposition to developing lethal carcinomas, the progression through well-defined stages, and the long-lasting interaction with the host microenvironment make BALB-neuT mice an appealing model for the evaluation of the role that immunosurveillance plays in inhibiting neu+ epithelial tumors. Previous studies on female BALB-neuT mice have shown that despite the absolute penetrance and aggressive tumorigenesis caused by neu transgene expression in the mammary glands and the existence of CD8+ T cell central immune tolerance to the neu caused by neu transgene expression in the mammary glands and the existence of CD8+ T cell central immune tolerance to the neu caused by neu transgene expression in the mammary glands and the existence of CD8+ T cell central immune tolerance to the neu caused by neu transgene expression in the mammary glands and the existence of CD8+ T cell central immune tolerance to the neu caused by neu transgene expression in the mammary glands and the existence of CD8+ T cell central immune tolerance to the neu caused by neu transgene expression in the mammary glands and the existence of CD8+ T cell central immune tolerance to the neu in male mice.

The progeny were genotyped to discriminate between normal (neu-/-) and neuT (neu+/+). A first line was generated from a BALB/c x F1 male mice received from the Peter MacCallum Cancer Centre (Melbourne, VIC, Australia) that was crossed with a BALB-neuT male re-derived in specific pathogen-free conditions by Charles River (Calco, Italy) and maintained at the Department of Clinical and Biological Sciences of the University of Torino (DCBS, Orbassano, Italy) (DCBS selection). A second line was generated later at the Molecular Biotechnology Center of the University of Turin (MBC, Torino, Italy) (MBC selection) from a BALB/c x F1 female originally from the Peter MacCallum Centre but re-derived in the National Research Centre for Allergy and Infectious Diseases/National Institutes of Health (Bethesda, MD) where a colony of these mice is maintained, by courtesy of Dr. Robert Wiltrout, that was crossed with a BALB-neuT male rederived by Biogem. Tumor onset was evaluated as previously described (13). BALB/c male mice knockout for the IL-15 gene (neu-/-IL-15-) were a gift from Dr. Silvia Bufone-Paus (Research Center Borstel, Borstel, Germany) to Dr. Pier-Luigi Lollini. All mice were maintained in specific pathogen-free conditions by guest on April 13, 2017 http://www.jimmunol.org/ Downloaded from

Materials and Methods

Mice

BALB-neuT male mice (13) from Biogen (Ariano Irpino, Italy) were crossed with pfp-/- BALB/c females (17). Heterozygous pfp-/- and neu-/- F1 male mice were then backcrossed with pfp-/- or pfp+ + BALB/c females. The progeny were genotyped to discriminate between normal (neu-/pfp+), pfp-/- (neu+/pfp+), those heterozygous for the neu transgene (neu+/pfp+), and those heterozygous for the neu transgene and pfp-/- (neu-/pfp+). A first line was generated from a BALB/c x pfp+ + female received from the Peter MacCallum Cancer Centre (East Melbourne, VIC, Australia) that was crossed with a BALB-neuT male re-derived in specific pathogen-free conditions by Charles River (Calco, Italy) and maintained at the Department of Clinical and Biological Sciences of the University of Torino approved the experimental plan.

Statistical differences were evaluated using GraphPad software 5.0 (GraphPad Software, San Diego, CA). The Mantel–Cox log-rank test was used to assess the differences in tumor incidence and overall survival. Differences in the frequency of tumors and mammary gland remnants were evaluated using the χ² test with a Yates correction. All the other statistical differences were assessed using the two-tailed unpaired Student t test.

Results

Pfp hampers the onset and shape the histology of neu+ salivary carcinomas in male mice

Salivary carcinomas are the prominent cause of death in neu+ males. The faster progression of these tumors in neu+/pfp- as compared with neu+/pfp+ males that was initially observed in a small number of males from the DCBS selection (Supplemental Fig. 1) spurred us to study the kinetics of these carcinomas in a larger number of males from the MBC selection. Salivary carcinomas became palpable significantly earlier in neu+/pfp- as compared with neu+/pfp+ mice (Fig. 1A; p < 0.0001). Whereas salivary carcinomas appeared from week 26 of age in neu+/pfp+ males, neu+/pfp- males had already started to develop salivary tumors at week 18. Similarly, overall survival was significantly shorter in neu+/pfp- than in neu+/pfp+ male mice (Fig. 1B; p < 0.0001).

Bone marrow transplantation and NK cell depletion

Eight-week-old neu+/pfp- male mice were exposed to a total dose of 7.8 Gy whole-body irradiation using a Gilardoni RADGIL x-ray generator (Gilardoni, Lecco, Italy). Twenty-four hours after irradiation, mice i.v. received 15 × 10⁶ bone marrow cells (BMCs) isolated from the femur and the tibia of pfp+ or neu+/pfp+ male mice and were then monitored for the appearance of salivary carcinoma. Nontransplanted, irradiated control mice died within 2 wk. To verify bone marrow engraftment, mice were bled and peripheral blood cells were stained with mAb anti-CD45 (130-091-811; Miltenyi Biotec), anti-B220-CD45R (558108), anti-CD90.1/Ty1.2 (553003), anti-CD8a (553033), anti-CD49b (553858) (all from BD Pharmingen), anti-CD11b (101206), and anti-CD4 (100528) (all from BioLegend) and analyzed by flow cytometry 1 mo after the injection of BMCs. Only transplanted mice displaying lymphoid and myeloid cell levels comparable to neu-/pfp- mice were evaluated. NK cell depletion was performed on neu+/pfp- males irradiated and reconstituted with BMCs from neu-/pfp- mice, starting from 30 d after BMC transplantation, and on untreated 6-wk-old neu+/pfp+ males. Mice received i.p. injections of 0.2 ml PBS containing a 1:20 dilution of anti-asialo GM1 rabbit anti-serum (Wako Pure Chemical Industries, Osaka, Japan) on days 0, 1, and 2 and then once a week until the salivary carcinoma became palpable. Controls were injected with normal rabbit serum (Life Technologies, Grand Island, NY).

Cytometry of tumor-infiltrating leukocytes

Freshly isolated tumor specimens of 7–8 mm mean diameter were dissociated as described previously (18) to obtain cellular suspensions that were treated with anti-CD4/CD32 (012458; BD Biosciences, San Jose, CA) and stained with anti-CD49b-PE (130-091-816), anti-CD45-VioGreen (130-097-294), anti-CD3a-VioBlue (130-094-360), anti-CD3e-FITC (130-092-962), anti-CD8a-FITC (130-155-569), anti-Th3-PE (Cedarlane, Calbo, Italy), and anti–γ-TCRPECy7 (118124; BioLegend, San Diego, CA). Samples were acquired and analyzed on the CyAn ADP using Summit 4.3 software (DakoCytomation, Heverlee, Belgium).

Salivary carcinomas are infiltrated by pfp-dependent effector immune cells

Various effectors immune cells are pfp-dependent (CD8+ αβ T, NK, NKT, and γδ T cells), most of which are CD3+ T, NK, or NK cells. In fact, infiltrating

Statistical analysis

Statistical differences were evaluated using GraphPad software 5.0 (GraphPad Software, San Diego, CA). The Mantel–Cox log-rank test was used to assess the differences in tumor incidence and overall survival. Differences in the frequency of tumors and mammary gland remnants were evaluated using the χ² test with a Yates correction. All the other statistical differences were assessed using the two-tailed unpaired Student t test.

Results

Pfp hampers the onset and shape the histology of neu+ salivary carcinomas in male mice

Salivary carcinomas are the prominent cause of death in neu+ males. The faster progression of these tumors in neu+/pfp- as compared with neu+/pfp+ males that was initially observed in a small number of males from the DCBS selection (Supplemental Fig. 1) spurred us to study the kinetics of these carcinomas in a larger number of males from the MBC selection. Salivary carcinomas became palpable significantly earlier in neu+/pfp- as compared with neu+/pfp+ mice (Fig. 1A; p < 0.0001). Whereas salivary carcinomas appeared from week 26 of age in neu+/pfp+ males, neu+/pfp- males had already started to develop salivary tumors at week 18. Similarly, overall survival was significantly shorter in neu+/pfp- than in neu+/pfp+ male mice (Fig. 1B; p < 0.0001).

At 8 wk of age, both neu+/pfp+ and neu+/pfp- males displayed small foci of atypical hyperplasia surrounded by numerous reactive cells in the salivary intercalated ducts and the serous acini (Fig. 2A and 2B, respectively). In neu+/pfp+ males the carcinomas that became palpable from week 26 of age appeared to have been uniformly generated by the clonofusion and evolution of multiple foci of ductal hyperplasia, and they were finally composed of solid lobules of uniform cells with no glandular differentiation (Fig. 2C), high mitotic activity (Fig. 2D), and high neu expression (Fig. 2E). In contrast, the quick outgrowth of poorly differentiated (Fig. 2F), highly proliferative (Fig. 2G), and highly neu+ (Fig. 2H) carcinomas in neu+/pfp- males was accompanied by the expansion of several areas of variously differentiated acinic carcinomas characterized by zones with clear cells (Fig. 2I) and others with large cells, resembling normal serous cells, organized in small nodules (Fig. 2L). Both areas were characterized by low proliferative activity (Fig. 2J, 2M) and high neu expression (Fig. 2K, 2N).

Salivary carcinomas are infiltrated by pfp-dependent effector immune cells

Various effectors immune cells are pfp-dependent (CD8+ αβ T, NK, NKT, and γδ T cells), most of which are CD3+ T, NK, or NK cells. In fact, infiltrating
cells in salivary carcinomas from both neu+/pfp− and neu+/pfp+ mice were predominantly CD3+ as shown by immunohistochemistry (Fig. 3A, 3B). A flow cytometric analysis was also performed to evaluate the relative amount of pfp-dependent effector immune cells in salivary tumors. As shown in Fig. 3C, CD8αβ T, γδ T, and NK cells (identified as CD3+CD49b+) were detected in the salivary tumors of both neu+/pfp+ and neu+/pfp− mice whereas CD3−CD49b− cells were present at very low percentages. The negligible presence of CD49b+ T cells suggests that these cells cannot be the major effectors that hamper neu+ salivary carcinogenesis whereas CD8αβT, γδ T, and NK cells might all contribute to this immunosurveillance phenomenon.

**T cells are not the principal players in immunosurveillance fight against neu+ salivary carcinomas**

To assess which pfp-dependent effector cell population was principally involved in hampering neu+ salivary carcinogenesis, we decided to perform bone marrow chimeras by reconstituting lethally irradiated 8-wk-old neu+/pfp+ male mice with BMCs from either neu−/pfp+ or neu−/pfp− male donors; some of the neu−/pfp+ reconstituted mice were also depleted of NK cells. Because the generation of γδ T cells mainly occurs during the fetal life, BMC reconstituted mice have CD8αβ T and NK cells, but are virtually devoid of γδ T cells (Supplemental Fig. 2). Salivary carcinoma onset occurred significantly earlier (p < 0.0001) in mice reconstituted with neu−/pfp+ BMCs (Fig. 4A) as compared with untreated neu−/pfp+ mice (Supplemental Fig. 3). These accelerated kinetics are due to the lethal irradiation and the time required by transplanted BMCs to reconstitute the mouse, but a possible contribution from the lack of γδ T cells cannot be ruled out. Nevertheless, salivary carcinomas arising in males reconstituted with neu−/pfp+ BMCs were uniformly poorly differentiated carcinomas with severe atypical features and a high proliferative rate (Fig. 4B, 4C), thus very similar to those that arise in untreated neu−/pfp+ males (Fig. 2C–E). Moreover, when mice reconstituted with neu−/pfp+ BMCs were depleted of NK cells, they displayed significantly anticipated salivary carcinoma onset (p = 0.02) as compared with nondepleted ones. In this case, the kinetics were very similar to what were found in mice reconstituted with neu−/pfp+ BMCs (Fig. 4A). The histological features of the salivary carcinomas that arose in mice reconstituted with neu−/pfp+ BMCs and depleted of NK cells (Fig. 4D–G) and those that arose in mice reconstituted with neu−/pfp− BMCs (not shown) were also very similar. Besides poorly differentiated (Fig. 4D) and highly proliferative areas (Fig. 4E), they also displayed several areas of differentiated acinic carcinomas with clear cell features, pronounced glandular differentiation (Fig. 4F), and lower proliferative rate (Fig. 4G), as found in untreated neu+/pfp− mice (Fig. 2F–N). Taken together, these data suggest that the main players in the immunosurveillance against neu+ salivary carcinomas may be NK cells, but certainly not CD8αβ T cells, and probably not γδ T cells either.

**Salivary carcinogenesis is delayed by NK cells**

To better evaluate the role of NK cells, neu+/pfp+ males were depleted of NK cells via the chronic administration of anti-asialo GM1 Abs. Salivary carcinoma onset was significantly faster in these mice than in neu+/pfp+ males treated with the control isotype and similar to that of neu−/pfp− mice (Fig. 5A, p = 0.003 and p = 0.4, respectively). Moreover, salivary carcinomas that arose in NK cell-depleted neu+/pfp+ males display areas with poor differentiation, high proliferation and neu expression (Fig. 5B–D) together with others with various degree of differentiation, lower proliferative rate, and high neu expression (Fig. 5E–J). These results confirm the key role of NK cells not only in making the kinetics of salivary carcinogenesis slower but also in doing the immune selection of premalignant cells that will become true cancer in salivary glands.

**Pfp blocks neu+ mammary carcinomas in male mice**

The onset of neu+ mammary carcinomas is a late event displayed by <20% of 1-y-old neu+/pfp+ males that survive salivary carcinomas. A surprisingly higher incidence of mammary cancer was first seen in a small number of neu+/pfp+ male mice from the DCBS selection (data not shown). When this observation was reexamined on a large number of males from the MBC selection, it was evident that >70% of neu+/pfp+ male mice display a mammary carcinoma within 1 y of age (Fig. 6A). Whole mount analysis of the most technically accessible second, third, and fourth mammary glands showed that microscopic mammary carcinomas were evident in 8% of 25- to 30-wk-old neu+/pfp+ males but in >36% of age-matched neu+/pfp− males. This reveals that even at this earlier time a 4-fold higher carcinoma incidence is microscopically evident in neu+/pfp− than in neu+/pfp+ males (Fig. 6B, p = 0.003). These carcinomas homogeneously consist of solid nodular aggregates that arise from ducts of persisting mammary remnants (Fig. 6C, 6D) composed of moderately differentiated atypical ductal neu+ cells surrounded by delicate vascularized stromal bundles and a moderate inflammatory infiltrate (Fig. 6E–H).

**Impaired mammary gland reabsorption in pfp-deficient male embryos**

The triggering of androgen receptors causes the regression of mammary sprouts that disappear during late embryogenesis (embryonic day 15.5) in most male mice glands (20). An evaluation of
The defective regression of mammary sprouts appears to be a major risk factor for mammary cancer in adult males. However, in neu+/pfp- males, only 30% of mammary remnants were associated with microscopic sprout structures, which instead were present in 75% of mammary sprouts persisting in neu+/pfp- males (Fig. 7D). These data show that the protection associated with the expression of the pfp gene derives from two distinct effects: a reduction in the number of males at risk due to the persistence of mammary remnants, and an efficient block of carcinogenesis in those adult neu- males that have mammary remnants.

Discussion

We have recently exploited the genetic predestination of female BALB-neuT mice to mammary carcinogenesis (23) to assess the weight of pfp-mediated (17) and complement-mediated (18) natural immunosurveillance toward neu- mammary carcinomas. We have now extended our observation to the role of pfp-mediated mechanism in the surveillance of salivary and mammary carcinomas that arise in BALB-neuT males (14). The data obtained show that the pfp deficiency: 1) reduces the tumor-free survival of these mice, 2) allows for the growth of more differentiated salivary tumor histotypes, and 3) impairs male mammary sprout reabsorption during embryogenesis.

The slow-growing salivary carcinomas are a common cause of death in adult neu+/pfp- males. About 70% of them die before reaching 1 y of age because of salivary tumor outgrowth. Salivary carcinogenesis is more aggressive in neu+/pfp- males. These pfp-deficient mice display shorter disease-free times and overall survival, with ~95% of them dying by 1 y of age. BMC reconstitution of lethally irradiated neu-/pfp- males excluded T cells performing a prominent role in this pfp-mediated phenomenon, whereas NK depletion experiments pointed to the central role of NK cell–expressed pfp in the inhibition of salivary carcinomas. These findings fit in well with our previous observation on the similar key role NK cells play in the control of mammary carcinogenesis in neu+/pfp- females (17) and with emerging data from epithelial human tumors that demonstrate a significant correlation between the reduced expression of pfp by NK cells and cancer progression in patients with pancreatic, gastric, and colorectal cancers (24).

The role of NK cells was not limited to affecting the pace of cancer progression, but also sculpted the histotype of salivary carcinomas that become clinically evident. The transforming neu transgene is expressed not only by several ductal cells but also by some cells of serous acini in the salivary glands of male mice during puberty. Areas of atypical hyperplasia of ductal and acinar structures are microscopically evident in the earlier stages of

FIGURE 2. Pfp deficiency permits the growth of less aggressive, more differentiated tumor histotypes. (A and B) H&E staining of salivary glands from 8-wk-old neu+/pfp- (A) and neu-/pfp- (B) male mice. Very similar areas of tubular (ductal) (green contour) and acinar (white contour) atypical hyperplasias are evident in both neu+/pfp- and neu-/pfp- male mice. Nodular aggregates of cells resembling cells of intercalated ducts and pseudo-acinar structures composed of enlarged and atypical cells with acinar features are evident. Numerous infiltrating inflammatory cells are in close contact with the hyperplastic lesions (black arrows). (C–N) Distinctive features of salivary carcinomas in 26- to 34-wk-old neu+/pfp- (C–E) and neu-/pfp- (F–M) male mice. In neu+/pfp- male mice sheets of poorly differentiated ductal cells with severe atypical features homogeneously form clinically evident salivary carcinomas (C) with high proliferative activity (D). Clinically evident carcinomas in neu+/pfp- mice display a similarly predominant poorly differentiated histotype (F) associated with large areas of clear cell (I) and well-differentiated (L) acinic carcinomas whose proliferative activity (J and M) is lower of that of poorly differentiated tumors (G). All the carcinoma histotypes are formed of highly neu+ cells (E, H, K, and N). Results are representative of nine neu+/pfp- and three neu-/pfp- salivary glands analyzed. (C, E, I, and L) H&E staining. (D, F, J, and M) PCNA immunostaining. (E, H, K, and N) neu immunostaining. Original magnification ×400; insets, ×1000.
FIGURE 3. Pfp-dependent effector immune cells equally infiltrate salivary tumors of both neu+/pfp− and neu+/pfp+ male mice. (A and B) Immunohistochemical staining of 16-wk-old neu+/pfp+ (A) and neu+/pfp− (B) salivary tumors for CD3 showing a significant amount of infiltrating CD3-reactive cells surrounding the hyperplastic lesions. Results are representative of nine neu+/pfp+ and three neu+/pfp− salivary glands analyzed. Original magnification ×400. (C) Cytofluorimetric analysis of T (CD3+ CD8+), NK (CD3− CD49b+), CD3+CD49b+, and γδ T (CD3−γδ−) cells in the salivary tumors of neu+/pfp− or neu+/pfp+ demonstrated that these cells infiltrate both tumors. Graph shows the percentage ± SEM of CD45+ cells expressing the different markers in neu+/pfp− (n = 3; filled bars) or neu+/pfp+ (n = 3; open bars) salivary tumors. Three independent experiments were performed and a representative one is shown.

carcinogenesis. However, only poorly differentiated monomorphic neu+ carcinomas of ductal origin sneak through the pfp-dependent mechanisms. In contrast, salivary carcinomas that become clinically evident in neu+/pfp− males display multiple minor areas of acinic neoplasia with a higher degree of differentiation and lower proliferative rate among the large areas of poorly differentiated carcinomas. Similarly, when lethally irradiated neu+/pfp− males were reconstituted with neu+/pfp BCMS, only poorly differentiated carcinomas were able to expand. In contrast, when lethally irradiated neu+/pfp+ males were reconstituted with neu+/pfp− BCMS, or with neu+/pfp+ BCMS but were depleted of NK cells, areas of neoplasia with a higher degree of differentiation and lower proliferative rate were again found to be components of the outgrowing tumors. Finally, areas of more highly differentiated neoplasia were also able to expand when otherwise untreated neu+/pfp− males were depleted of NK cells. These data further support the importance of NK cells not only in immunosurveillance, but also in the immunoediting of epithelial cancer.

This pfp-dependent selection of tumor histotype also corroborates data on neoplastic stem cells’ increased ability to give rise to tumors when injected into immunocompromised, as compared with normal, mice (26, 27). Although a few neoplastic stem cells are able to give rise to a tumor in mice with an efficient immune system, many others are able to outgrow in those that are immunocompromised. This implies that malignant cells with stem cell properties are endowed with a different degree of penetrance, suggesting that the cell differentiation expressed by tumors may not only be the result of the transformation of cells with distinctive stem cell features, but also of the action of transforming stimuli on differentiated cells that are able to regain stem cell functions. Those with a higher degree of differentiation, which are therefore less aggressive, such as transformed salivary acinar cells, may be blocked by immune surveillance mechanisms, whereas those that are less differentiated, such as mammary and salivary transformed ductal cells, are only delayed in their progression.

Finally, pfp-deficient BALB-neuT males also display a 4-fold higher incidence of mammary carcinomas, showing the importance of pfp-dependent immunosurveillance against aggressive tumors with low penetrance. This surprising finding may result from both immune mechanisms and altered pfp-dependent mammary morphogenesis. In both neu+/pfp+ and neu+/pfp− males, moderately

FIGURE 4. Salivary carcinogenesis onset is affected by NK cells. (A) A Kaplan–Meier curve showing the incidence of salivary tumors in neu+/pfp+ male mice reconstituted with neu+/pfp− BCMS (n = 26; black dotted line), with neu+/pfp− BCMS (n = 29; black solid line), or with neu+/pfp+ BCMS and treated with anti-asialo GM1 Abs (n = 7; gray solid line). *p = 0.02, Mantel–Cox log-rank test. (B–G) Histology [(B, D, and F) H&E staining] and immunohistochemistry [(C, E, and G) PCNA immunostaining] showed that salivary carcinomas in neu+/pfp+ males reconstituted with neu+/pfp− BCMS are poorly differentiated with severe atypical features (B) and a high proliferative rate (C) whereas those in males reconstituted with neu+/pfp− BCMS and treated with anti-asialo GM1 Abs display a predominant poorly differentiated histotype (D) and a high proliferative rate (E) associated with areas of more differentiated acinic carcinoma with clear cell features (F) and lower proliferative activity (G). Results are representative of four salivary tumors analyzed for each experimental group. Original magnification ×400.
differentiated neu+ cells that originate from the ducts of the rudimental mammary gland sprouts make mammary carcinomas. Consequently, the persistence of these rudiments in a few areas in male mammary pads is a major risk factor. Microscopic examination of a large number of mammary areas showed that the frequency of persisting mammary remnants was almost twice as
Defective regression of mammary sprouts and potential role of γδ T cells in the involution of mammary glands in male mice. (A) Frequency of mammary remnants found in the areas of second, third, and fourth mammary glands in 20- to 30-wk-old male mice, as assessed by whole mount (neu+/pfp+, n = 292; neu+/pfp−, n = 196; neu−/pfp+, n = 150; neu−/pfp−, n = 168; neu−/IL-15−, n = 126). *p < 0.05, **p < 0.01, χ² test with a Yates correction. (B and C) Immunohistochemistry for γδ T cells in female (B) and male (C) mammary bud at embryonic day 14.5. The bud is fully formed. The epithelial cells are arrayed in an inverted bulb shape. The mesenchymal cells are arranged in four to five layers in a radial fashion around the epithelial cells. A couple of γδ T cells (arrows) are visible only close the male bud. Original magnification ×400. (D) Frequency of mammary remnants displaying microscopic tumors in whole mount examined from 20- to 30-wk-old neu+/pfp+ (n = 50) and neu+/pfp− (n = 36) male mice. **p < 0.01, χ² test with a Yates correction.

Because the frequency of male mice with at least one mammary area containing mammary remnants is almost twice as high among neu+/pfp− than in neu+/pfp+ males, the lack of pfp appears to play a marked role in increasing the probability of developing mammary cancer. The fact that the incidence of mammary cancer is 4-fold times higher in neu+/pfp− males than in neu+/pfp+ males suggests that the higher risk of mammary cancer, caused by defective mammary rudiment regression, is further enhanced by the lack of pfp-dependent immunosurveillance. In effect, the number of mammary remnants associated with a microscopic tumor is ~2.5-fold higher at weeks 20–30 of age in neu+/pfp− as compared with neu+/pfp+ males.

In conclusion, our data support the existence of a critical role played by pfp-expressing NK cells in both immunosurveillance and immunoediting of neu+ epithelial cancers. They markedly delay the onset of mammary and salivary carcinomas and their growth rate, but they also sculpt the differentiation stage of salivary carcinomas. Additionally, our findings have unveiled the previously unsuspected involvement of pfp in male mammary gland reabsorption during embryogenesis, suggesting the existence of a possible role for γδ T cells in this phenomenon. Collectively, these findings provide further proof of the multiple roles that pfp-mediated mechanisms fulfill in cancer control and may be important for the development of NK cell–based therapeutic strategies.

**Acknowledgments**
We thank Dr. Dale Lawson for revision and editing of the manuscript, Dr. Simona Rolla for helpful assistance in the establishment of both colonies of neu+/pfp−, and Dr. Paolo E. Forni for technical help in studying the development of mammary glands in mouse embryos.
Disclosures
The authors have no financial conflicts of interest.

References