Targeting galectin-1 overcomes breast cancer-associated immunosuppression and prevents metastatic disease

Tomás Dalotto-Moreno¹, Diego O. Croci¹, Juan P. Cerliani¹, Verónica C. Martinez-Allo¹, Sebastián Dergan-Dylon¹, Santiago P. Méndez-Huergo¹, Juan C. Stupirski¹, Daniel Mazal², Eduardo Osinaga³, Marta A. Toscano¹, Victoria Sundblad¹, Gabriel A. Rabinovich¹,⁴* and Mariana Salatino¹ *

¹Laboratorio de Inmunopatología, Instituto de Biología y Medicina Experimental (IBYME), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), C1428 Buenos Aires, Argentina.
²Servicio de Anatomía Patológica, Centro Hospitalario Pereira Rossell, C11600 Montevideo, Uruguay.
³Departamento de Inmunobiología, Facultad de Medicina, C11800 Montevideo, Uruguay.
⁴Departamento de Química Biológica, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, C1428, Buenos Aires, Argentina.

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Footnotes:
* G.A.R. and M.S. should be considered as co-senior authors.

Correspondence:
Mariana Salatino, Ph.D.
Laboratorio de Inmunopatología. IBYME
Vuelta de Obligado 2490, C1428, Buenos Aires, Argentina
E-mail: mariansalatino@gmail.com
ABSTRACT

Galectin-1 (Gal1), an evolutionarily conserved glycan-binding protein, contributes to the creation of an immunosuppressed microenvironment at sites of tumor growth. In spite of considerable progress in elucidating its role in tumor-immune escape, the mechanisms underlying the inhibitory functions of Gal1 remain obscure. Here we investigated the contribution of tumor Gal1 to tumor growth, metastasis and immunosuppression in breast cancer. We found that the frequency of Gal1+ cells in human breast cancer biopsies correlated positively with tumor grade, while specimens from patients with benign hyperplasia showed negative or limited Gal1 staining. To examine the pathophysiologic relevance of Gal1 in breast cancer, we used the metastatic mouse mammary tumor 4T1, which expresses and secretes substantial amounts of Gal1. Silencing Gal1 expression in this model induced a marked reduction in both tumor growth and the number of lung metastases. This effect was abrogated when mice were inoculated with wild-type (WT) 4T1 tumor cells in their contralateral flank, suggesting involvement of a systemic modulation of the immune response. Gal1 attenuation in 4T1 cells also reduced the frequency of CD4+CD25+ Foxp3+ regulatory T (T_{reg}) cells within the tumor, draining lymph nodes, spleen and lung metastases. Further, it abrogated the immunosuppressive function of T_{reg} cells and selectively lowered the expression of the T-cell regulatory molecule LAT (linker for activation of T cells) on these cells, disarming their suppressive activity. Taken together, our results offer a preclinical proof of concept that therapeutic targeting of Gal1 can overcome breast cancer-associated immunosuppression and can prevent metastatic disease.
PREMIS

Findings offer preclinical genetic validation to block an immunosuppressive lectin commonly expressed in aggressive cancers, as a strategy to reverse immune escape and blunt metastatic progression.
INTRODUCTION

The breast cancer microenvironment is composed of innate and adaptive immune components that actively influence the anti-tumor response (1). The current view supports the idea that immune cells efficiently protect the host from arising tumors; however once a primary tumor is generated, the tumor-associated immune cell network can paradoxically promote tumor growth and metastasis (2).

Lectin-glycan interactions have emerged as critical determinants of tumor progression (3). Galectins, a family of endogenous lectins abundantly expressed in tumor microenvironments, can regulate transformation, angiogenesis, cell adhesion and tumor-immune escape (4-7). Galectin-1 (Gal1), a ‘proto-type’ member of this family, binds to multiple N-acetyllactosamine (Galβ1-4GlcNAc) units decorating complex N- and O-glycans on cell surface glycoproteins (8). Research from our laboratory has recognized an essential role for Gal1 as an immunoevasive mechanism in human and mouse melanoma (9). These observations were further confirmed in mouse lung adenocarcinoma (10-11), and in human cancers including Hodgkin lymphoma (12-13), neuroblastoma (14), head and neck squamous cell carcinoma (15), pancreatic carcinoma (16), glioma (17) and T-cell lymphoma (18), suggesting that targeting the Gal1-glycan axis might contribute to overcome immunosuppression and potentiate immunotherapeutic approaches. Interestingly, Gal1 was identified as a tumor-associated protein capable of delineating the metastatic potential of human breast carcinoma (19-20). Importantly, stromal cell expression of Gal1 is up-regulated in invasive breast carcinoma as compared to in situ carcinoma, showing a positive correlation with T or TNM progression stages (21).

Extracellularly, Gal1 acts by cross-linking glycosylated receptors on the surface of immune cells and modulating their survival, cytokine production and trafficking (3, 22-25). This glycan-binding protein inhibits immune effector functions by shifting the balance toward a Th2 cytokine
profile (9, 23), by selectively deleting Th1 and Th17 cells (22) and by promoting the differentiation of tolerogenic dendritic cells (DCs) (11, 14, 26). Moreover, Gal1 facilitates the expansion of IL-10-producing T regulatory type-1 (Tr1) cells (23, 26-27) and contributes to the immunosuppressive activity of CD4⁺CD25⁺FoxP3⁺ T regulatory (T_{reg}) cells (28-29).

With the ultimate goal of validating the Gal1-glycan axis as a novel therapeutic target, in the present study we examined the contribution of Gal1 to breast cancer-induced immunosuppression, tumor growth and metastasis. We used the highly metastatic mouse mammary tumor model 4T1, which recapitulates several features of advanced human breast cancer including lack of hormone receptors and the ability to generate spontaneous lung and lymph nodes metastasis (30). Inhibition of Gal1 expression not only prevented tumor growth but also suppressed the development of lung metastasis and disarmed the suppressive activity of T_{reg} cells through mechanisms involving downregulation of the linker for activation of T cells (LAT), an adaptor protein involved in T-cell receptor (TCR) signaling. Thus, targeting Gal-1-glycan interactions in the breast cancer microenvironment represents a novel therapeutic approach with significant translational potentiality.
MATERIALS AND METHODS

Mice and Human Samples

Female BALB/c mice or C57BL/6 (8-12 weeks) were housed at the animal facility of the Institute of Biology and Experimental Medicine (IBYME) according to NIH guidelines. Formalin-fixed, paraffin-embedded tumor sections were obtained from the Department of Pathology, Centro Hospitalario Pereira Rossell, Montevideo, Uruguay. Protocols were approved by the Institutional Review Board of IBYME.

Immunohistochemistry

Paraffin-embedded tissues were sectioned at 4 μm and mounted. After deparaffinization, tissues were stained with rabbit anti-Gal1 antibody (Ab) (9) (1:500 or 1:400 for human or mouse respectively) or anti-Foxp3 (e-Bioscience; 1:100) and revealed using the Vectastain Elite ABC kit (Vector). Staining was scored as: 0 (negative), 1 (0-30% positive), 2 (30-60% positive) or 3 (more than 60% positive) and classified as weak (0-1) or strong (2-3).

Cells and knockdown (KD) clones

4T1 and B16 cells were acquired from the American Type Culture Collection (ATCC) and were maintained in DMEM 10% FCS (Gibco). Three Gal1-specific and one scramble shRNAs were cloned into the pSIREN-RetroQ vector (12). Viral production was performed using RetroPack PT-67 packaging cell line (BD Clontech) according to manufacturer’s instructions. 4T1 cells were infected using viral supernatants plus 8 μg/ml polybrene. Clones were selected with puromycin (5 μg/ml) by limited dilution.

Immunoblotting
Cells were lysed (NH₄Cl 150 mM, KHCO₃ 10 mM, EDTA 0.01 mM) and proteins were resolved by SDS-PAGE, blotted and probed with Ab against Gal1 (1:2000), LAT (11B.12, 1:1000; Abcam), Gal3 (B2-C10, 1:500; provided by Fu-Tong Liu), Foxp3 (eBio7979, 1:1000; e-Biosciences) or Actin (Pan Actin Ab-5, 1:2000; Neomarker). Protein bands were analyzed with the ImageJ 1.440 analysis software (NIH).

**In vivo tumor models**

BALB/c mice were challenged s.c. in the abdominal mammary gland with 4T1 and/or 4T1 KD cells (15000 cells/50µl) in serum-free PBS (n=5). Tumor diameter was calculated as W² x L /2 where W=width and L=length. Mice were sacrificed at day 28. Lung metastases were counted after fixing lungs with Bouin reactive or quantified by the clonogenic assay (30). B16 cells (1x10⁶/50 µl) were inoculated s.c. in C57BL/6 or 4T1 tumor-bearing BALB/c mice (n=4).

**In vitro proliferation assays**

*In vitro* tumor cell growth was measured by the MTS assay (9) and by a clonogenic assay. Briefly, cells were seeded (200 cells/ P6 well). After two weeks, media was removed and colonies were stained with crystal violet. For T-cell proliferation, tumor-draining lymph nodes (TDLN) cells or spleen cells (20000/well) were restimulated for 72 h with anti-CD3 and anti-CD28 monoclonal antibodies (mAb) (R&D) and 4T1 lysates. Proliferation was assessed by [³H] -thymidine incorporation in 96-well plates.

**Flow cytometry and adoptive transfer**

Frequency of T_reg cells was determined by using the mouse T_reg staining kit (eBioscience) and analyzed on a FACSARia (BD Biosciences) using a FlowJO software. CD4⁺ T lymphocytes were
isolated by sorting using a PE-labeled anti-CD4 Ab (eBioscience). T_{reg} cells were purified by sorting with anti-CD4, anti-CD25 and anti-FR4 mAb (all from eBioscience). For adoptive transfer, sorted T_{reg} cells (300000 cells) from TDLN were labeled with CFSE (0.5 µM) and intravenously injected in KD tumors-bearing mice (n=4).

**Suppression assay**

Sorted CD4^{+}CD25^{-} responder T (T_{resp}) cells and CD4^{+}CD25^{+}FR4^{+} T_{reg} cells were stimulated with anti-CD3 and anti-CD28 mAb plus IL-2 and mixed at the indicated ratio as described (31). Proliferation was assessed by [³H]-thymidine incorporation in 96-well plates.

**In vitro differentiation of T_{reg} cells**

T_{reg} cells were differentiated for 4 days from sorted naïve T cells (CD62L^{+}) in serum-free RPMI in the presence of TGF-β_{1} (3 ng/ml) and IL-2 (100 U/ml) with or without conditioned media (CM 1:10, 1:50 and 1:100) collected from 4T1 WT or KD cells cultured in p60 plates in 2 ml serum-free RPMI medium for 18 h.

**ELISA**

Tumor-draining lymph node (TDLN) cells or spleen cells (200000 cells/well) were restimulated ex vivo for 72 h with anti-CD3 and anti-CD28 mAb and supernatants were analyzed by ELISA for detection of mouse IFN-γ and IL-10 (BD Biosciences) and IL-5 (R&D). Soluble Gal1 was determined using an in house-made ELISA as described (32).

**Real-time PCR**
RNA was obtained using TRIZOL reagent following manufacturer’s instructions. DNA contamination was removed using DNAsel I. cDNA was synthesized using Super Scrip III Reverse Transcriptase (Invitrogen). For real time, the SYBR Green PCR Master Mix was used with an ABI System 7500 (Applied Biosystem). Primers: Gal1 5’-TCAGCCTGGTCAAAGGTGAT-3’ 5’- TGAACCTGGGAAAAGACAGC-3’, Foxp3 5’-ACTGGGGTCTTCTCCCTCAA-3’ 5’- CGTGGGAAGGTGCAGAGTAG-3’, LAT 5’-TGCCGTGAGTTGCCAGTCTCCT-3’ 5’- AGCAGGTGTTGGGGGACGG-3’, GAPDH 5’-CAGAACATCATCCCTGCAT-3’ 5’- GTTCAGCTCTGGGATGACCTT-3’. A commercial kit was used to screen mouse genes implicated in T cell anergy and tolerance RT2 Profiler PCR array (PAMM-074, SA Biosciences). Screening of the 84 pathway-specific genes was performed in duplicate (n=4).

Statistical analysis

Prism software (GraphPad) was used. Two groups were compared with the Student’s-\(t\) test for unpaired data. One-way ANOVA Tukey or Bonferroni post-tests were used for multiple comparisons. Nonparametric analysis was performed using Kruskal-Wallis test. \(P\) values of 0.05 or less were considered significant.
RESULTS

Expression of Gal1 correlates with the aggressiveness of human breast tumors and is up-regulated in the mouse metastatic 4T1 breast cancer model

We first examined the expression of Gal1 in human breast carcinoma tissues. Immunohistochemical analysis of a collection of human breast adenocarcinomas (n=55 patients) revealed expression of Gal1 in both epithelial and stromal cells (Figure 1A). Notably, a positive correlation was found between the number of Gal1+ cells and the Scarff-Bloom-Richardson scale (histopathological grade 2 and 3) (Figure 1B). On the contrary, Gal1 staining was barely detectable in epithelial cells from benign breast hyperplasia (Figure 1A), suggesting up-regulated expression of this lectin during mammary carcinogenesis. Similarly, we observed higher expression of Gal1 in the mouse 4T1 breast tumor compared with normal adjacent mammary gland, and other breast cancer cell lines including the hormone-dependent T47D and MCF-7 (human) and C4HD (mouse) cell lines (Figure 1C and D). Moreover, the 4T1 cell line expressed Gal1 at similar levels than the highly metastatic MDA-MB-231 cell line, highlighting 4T1 as an optimal tumor model for studying the relevance of this lectin in breast cancer.

Knocking down Gal1 in breast cancer decreases tumor burden and prevents lung metastasis

To study the role of Gal1 in breast cancer, we knocked down Gal1 in 4T1 cells by transduction with a retroviral vector containing a mouse Gal1-specific shRNA sequence (4T1-KD). Clone shRNA3.7 was selected as the clone with the lowest Gal1 expression (Figure 2A). Scrambled-transduced cells (Scr1) were used as controls. The introduced shRNA specifically targeted Gal1 as expression of galectin-3 (Gal3), another member of the galectin family, was not affected (Figure 2B). Secretion of Gal1 to CM was also impaired (Figure 2C and D). Mice inoculated with 4T1 knockdown cells (shRNA3.7) showed a considerable reduction of tumor growth compared to mice...
receiving 4T1 Scr1 control cells (Figure 2E). The observed anti-tumor effect could not be attributed to intrinsic differences in cell proliferation rates, as Gal1-sufficient (WT and Scr1) 4T1 cell lines showed no growth advantage in vitro over Gal1 knockdown clones (Figure 2F). The Scr1 clone showed an in vivo behavior similar to that of the parental 4T1 cell line and was therefore used as control. Remarkably, Gal1 silencing almost completely suppressed lung metastasis, as reflected by a lower number of colonies (Figure 2G), and a reduced tumor burden in the lungs (Figure 2H). Interestingly, in lung tissue from mice bearing 4T1 WT tumors, Gal1 was selectively expressed in metastatic lesions (Figure 2I) and was barely detected in the surrounding non-tumoral parenchyma, suggesting that Gal1 could serve as a biomarker capable of detecting emerging metastatic foci. Notably, disruption of Gal1 expression did not impair the invasive capacity of the 4T1 cell line as all clones migrated equivalently in in vitro invasion assays (Figure 2J). Thus, targeting Gal1 in the breast cancer microenvironment restrains tumor growth and prevents lung metastasis.

**Tumor Gal1 promotes immunosuppression in breast cancer**

As 4T1 breast cancer cells promote the expansion of T\(_{\text{reg}}\) cells which sustain the development of lung metastasis (33), we used this model to investigate whether Gal1 blockade may influence anti-tumor responses by modulating the tumor-associated T\(_{\text{reg}}\) cell compartment. We found a diminished frequency of T\(_{\text{reg}}\) cells (CD4\(^{+}\)CD25\(^{+}\) Foxp3\(^{+}\)) in the spleen, TDLN, primary tumor and lungs of mice bearing Gal1 KD tumors as compared with their WT counterpart (Figure 3A-E). Moreover, we found reduced differentiation toward a T\(_{\text{reg}}\) cell phenotype when naïve T cells were cultured in the presence of CM from 4T1 KD cells as compared to naïve T cells exposed to CM from Gal1-sufficient cells (Figure 3F), suggesting that a Gal1-enriched microenvironment favors the
generation of inducible T\(_{\text{reg}}\) cells. Notably, this effect was observed when naïve T cells were exposed to CM from 4T1 cells either in the presence or absence of exogenous TGF-β (Figure 3F).

It has been proposed that Th2-type associated inflammation contributes to breast cancer progression (34). As Gal1 promotes Th2 responses in autoimmune settings (22-23), we asked whether impaired tumor growth and metastasis after Gal1 blockade were associated with a reduced Th2-cytokine profile. Cells isolated from the spleen or TDLN from mice bearing KD 4T1 tumors produced lower amounts of IL-5 and IL-10 and showed reduced IL-10/IFN-γ ratio than their WT counterpart (Figure 3G). Moreover, \textit{in vitro} culture of TDLN T cells isolated from mice bearing Gal1-deficient 4T1 tumors displayed more robust proliferation than T cells from mice bearing WT tumors (Figure 3H). Thus, tumor-derived Gal1 contributes to delineate an immunosuppressive breast cancer microenvironment characterized by increased frequency of T\(_{\text{reg}}\) cells and a shift toward a Th2 cytokine profile.

**Targeted disruption of Gal1 eliminates tumor-mediated immunosuppression \textit{in vivo}**

To further dissect the mechanisms underlying the pro-tumoral effects of Gal1, we examined whether expression of this lectin in the tumor microenvironment influences systemic immunosuppression. We hypothesized that if a Gal1-deficient tumor is inoculated simultaneously with a Gal1-sufficient tumor in the contralateral side, tumor-derived Gal1 will provide the tolerogenic milieu necessary to systemically blunt effector T cell responses. As a result, the Gal1 KD tumor will behave as a WT tumor in terms of promotion of tumor growth and metastasis. Notably, inoculation of a WT tumor markedly influenced the behavior of a contralateral KD tumor, which grew progressively as its WT counterpart (Figure 4A). On the contrary, when mice bearing a KD tumor were inoculated in the opposite flank with another KD tumor, both tumors grew slowly (Figure 4A). The number of metastatic foci in lungs of mice bearing a WT/KD tumor combination
was similar to that observed in the WT/WT group and was considerably enhanced when compared to the KD/KD group (Figure 4B). Remarkably, splenocytes from mice bearing WT/WT or WT/KD tumors failed to proliferate \textit{ex vivo} in response to tumor antigens while splenocytes isolated from KD/KD tumors showed robust proliferation in response to 4T1 cell lysates (Figure 4C). Notably, the frequency of T\textsubscript{reg} cells present within the Gal1 KD TDLN was as elevated as the WT TDLN (Figure 4D). Collectively, these results indicate that the presence of a WT tumor promotes a dominant systemic immunosuppression that thwarts the development of an effective anti-tumor response.

Previous studies showed that mice inoculated with 4T1 tumors exhibit impaired rejection of allogeneic tumors, suggesting a compromised effector T-cell function (35). We examined whether targeting Gal1 in 4T1 breast tumors could restore the ability of BALB/c mice to reject a contralateral allogenic B16 melanoma. For this, BALB/c mice which have been inoculated with 4T1 WT or KD tumors were challenged 21 days later with B16 melanoma cells (background C57BL/6) in the contralateral flank. As previously reported (35), only one out of four B16 tumors was rejected in mice bearing 4T1 WT tumors. In sharp contrast, all B16 tumors were rejected in mice bearing Gal1 KD 4T1 tumors. As expected, B16 tumors grew progressively in C57BL/6 mice (Figure 4E). Thus, targeting Gal1 locally in the tumor microenvironment successfully overcomes systemic immunosuppression displayed by 4T1 breast tumors.

**Targeting tumoral Gal1 disarms the immunosuppressive activity of T\textsubscript{reg} cells**

The contribution of Gal1 to the immunosuppressive activity of breast tumors prompted us to investigate whether targeting tumoral Gal1 might affect not only the frequency of T\textsubscript{reg} cells, but also their suppressive capacity. T\textsubscript{reg} cells sorted from TDLN of Gal1-deficient tumors showed reduced suppressive activity over CD4\textsuperscript{+}CD25\textsuperscript{−} T\textsubscript{Resp} cells as compared with T\textsubscript{reg} cells isolated from a
Gal1-enriched microenvironment (WT tumors) (Figure 5A). Thus, targeting Gal1 expression in the tumor microenvironment attenuates $T_{reg}$ cell suppressive activity.

It has been demonstrated that 4T1 tumors progress toward a metastatic phenotype by influencing the immune composition of the lung microenvironment (36). To test this possibility, we analyzed gene expression profiles of CD4$^+$ T cells infiltrating lungs colonized with WT or Gal1 KD 4T1 metastasis. We used a qRT-PCR array for screening genes functionally associated with immune tolerance and anergy (data not shown). Notably, among other discrete changes, we observed a consistent altered expression of $Lat$, a gene that encodes a tyrosine phosphorylated transmembrane adaptor protein which expression is associated with the suppressive activity of $T_{reg}$ cells (37-38). Recent findings demonstrated that inhibition of LAT in mice leads to impaired immune tolerance due to diminished suppressive activity of $T_{reg}$ cells (37). Consistent with this observation, we observed substantial downregulation of LAT expression in CD4$^+$ T cells isolated from pulmonary metastasis, primary tumor and spleen of mice bearing 4T1 Gal1 KD tumors (Figure 5B). Particularly, LAT expression was considerably lower in $T_{reg}$ cells isolated from metastatic lungs (Figure 5C) or from TDLN of mice bearing Gal1 KD tumors (Figure 5D). Moreover, LAT expression was lower in $T_{reg}$ cells differentiated in vitro in the presence of TGF-$\beta$ and CM from 4T1 KD cells compared to those exposed to CM from 4T1 WT cells (Figure 5E). However LAT expression was unaltered during tumor growth in the CD4$^+$CD25$^-$ non-$T_{reg}$ cell population (Figure 5D).

To further confirm that $T_{reg}$ cells mediate tumor-induced immunosuppression and metastasis in Gal1-sufficient 4T1 tumor-bearing mice, we conducted a series of in vivo adoptive transfer experiments. Sorted $T_{reg}$ cells isolated from TDLN of WT or Gal1 KD 4T1 tumors were intravenously injected in KD or WT tumor-bearing mice. Prior to inoculation sorted $T_{reg}$ cells were labeled with CFSE for tracking purposes. Although we could find no differences in tumor growth rates (Figure 5F), metastatic foci were significantly increased when mice bearing Gal1 KD tumors
were adoptively transferred with T\textsubscript{reg} cells obtained from WT TDLN (Figure 5G). Transfer of WT T\textsubscript{reg} cells did not alter tumor growth or metastasis in mice bearing WT tumors (Figure 5F and G). At day 28 CFSE staining was positive on T\textsubscript{reg} cells collected from the spleen, TDLN, primary tumor and metastatic lungs (data not shown). Thus, targeting Gal1 expression in primary breast tumors abrogates lung metastasis through mechanisms involving, at least in part, a reduced suppressive activity of T\textsubscript{reg} cells associated to downregulation of LAT.
Discussion

Gal1, an endogenous β-galactoside-binding lectin, has emerged as key a regulator of immune tolerance and homeostasis (3, 39). As Gal1 is overexpressed in a wide range of tumors and tumor-associated stroma, and its expression correlates with impaired anti-tumor responses, it has been hypothesized that Gal1 contributes to create an immunosuppressive microenvironment at sites of tumor growth (3). Here we show that Gal1 favors the tumorigenic and metastatic potential of 4T1 breast tumors. Breast cancer cells producing low amounts of Gal1 were less tumorigenic and failed to metastasize to lungs through mechanisms involving inhibition of T_{reg} cell expansion and/or downmodulation of their suppressive activity. In addition, we found selective inhibition of LAT expression in T_{reg} cells from mice bearing Gal1 KD tumors, suggesting that silencing Gal1 might contribute to interrupt the T cell receptor (TCR)/LAT signaling and impair T_{reg} cell function.

Previous studies indicated that breast cancer-derived Gal1 could control tumor progression (21, 40-41). Using the mouse mammary adenocarcinoma LM3 and the human breast tumor line MCF-7, we previously found that Gal1 is under the control of TGF-β, suggesting that both mediators might act in concert to counteract antitumor responses (42). Importantly, in samples of human breast carcinoma tissues, higher Gal1 expression was observed in stromal cells of invasive compared to in situ carcinomas (21). The authors found that Gal1 expression in the tumor stroma positively correlated with T and TNM stages in a selected cohort of breast cancer patients (21). Moreover, Gal1 was identified as an abundant protein in the tumor interstitial fluid in breast cancer tissues as compared to normal interstitial fluid (43), suggesting that tumor-secreted Gal1 could serve as a potential biomarker for early detection of the disease.

Research over the past few years has revealed novel insights into the mechanisms underlying the immunoregulatory functions of Gal1. We previously found that Gal1-glycan interactions negatively regulate the survival of effector Th1 and Th17 cells (22). As Th1 and Th17
responses are often associated with anti-tumor immunity (2), Gal1 effects may contribute to enhance protumoral Th2 responses. In addition Gal1 acts by promoting the differentiation of IL-27-producing DCs which in turn trigger the expansion of IL-10-producing type-1 T regulatory (Tr1) cells (26). Here we found that inhibition of Gal1 expression in 4T1 breast cancer cells targets the FoxP3+ T_{reg} cell compartment and leads to decreased IL-10 and IL-5 production, suggesting that tumor-derived Gal1 could influence the metastatic niche in the lung by inducing a Th2- and T_{reg} cell-dominant response which facilitates metastasis formation.

Here we found that Gal1-sufficient 4T1 breast tumor cells promote tumor growth and metastasis by increasing the frequency of tumor-associated and systemic CD4+CD25+Foxp3+ T_{reg} cells. Targeting tumoral Gal1 induced a reduction in the frequency of T_{reg} cells in the spleen, lymph nodes, primary tumor and metastatic lungs. In this regard, we previously reported the ability of recombinant Gal1 to promote the differentiation of CD4+CD25+ T_{reg} cells in vitro (12). Here we demonstrated the capacity of tumor-derived Gal1 to increase the relative abundance and/or expansion of peripheral T_{reg} cells in vivo and to modulate their suppressive capacity. Our findings suggest a possible scenario in which elimination of Gal1-induced immunosuppression and T_{reg} cell expansion in the primary tumor could be reproduced at distance in the metastasis target organ.

Alternatively, decreased number of lung metastasis, in addition to the lack of Gal1 expression in the few remaining metastatic foci, might prevent tumor-induced differentiation of T_{reg} cells in the lungs.

Interestingly, we found considerable downregulation of the protein adaptor LAT in T_{reg} cells isolated from TDLN, spleen, primary tumors and lungs when Gal1 was suppressed. The transmembrane adaptor LAT binds Grb2, GADS, and phospholipase C-γ1 (PLC-γ1) (44) and is essential for T-cell activation, thymocyte development and immune cell homeostasis. Mice harbouring a knock-in mutation in LAT at the PLC-γ1-binding site show severe autoimmune
disorders (45-46). In addition, it has been demonstrated that proximal signals downstream of the TCR, specifically the LAT–PLC-γ1 interaction, controls FoxP3 expression and development of Treg cells (47). More recently, Chuck and colleagues demonstrated that binding of LAT to PLC-γ1 is essential for sustaining the suppressive function of CD4^+CD25^+Foxp3^+T_{reg} cells (37), highlighting the importance of LAT as an inhibitory checkpoint during immune cell homeostasis. In agreement, our findings show that T_{reg} cells from mice bearing Gal1 KD tumors express lower LAT levels and have reduced suppressive activity. Thus, the more effective anti-tumor response observed in mice bearing Gal1 KD tumors could be explained, at least in part, by the reduced expression of LAT in T_{reg} cells and their impaired suppressive activity. In line with our findings, LAT-deficient T_{reg} cells were unable to suppress the expansion of conventional effector T cells (37-38), an effect that recapitulates T_{reg} cell inhibition observed upon Gal1 blockade. The precise mechanisms underlying the cross-talk between Gal1 and LAT expression in T_{reg} cells remain to be investigated. As Gal1 can interact with the TCR complex and influence downstream signaling pathways on effector T cells (48), it would be interesting to examine whether tumoral Gal1 may affect TCR signalling in T_{reg} cells.

The identification of Gal1 as a pivotal mediator of cancer-induced immunosuppression and a critical factor responsible of thwarting immunotherapeutic strategies opens new avenues in cancer immunotherapy. Our study demonstrates, in a breast cancer model, that blocking Gal1 in the primary tumor abrogates the development of distant lung metastasis through mechanisms involving reversion of local and systemic immunosuppression. Several therapeutic strategies have been proposed to block the detrimental effects of Gal1-glycan interactions; however none of these strategies are fully-specific for Gal1. For example, thiodigalatoside, a non-metabolizable small disaccharide that binds Gal1, prevents some tumor promoting effects of this endogenous lectin, including angiogenesis and immune escape (40-41, 49-50). However, this compound also
binds and inhibits the action of other members of the galectin family through blockade of the carbohydrate-recognition domain (49-50). With the long-term goal of translating basic findings into potential clinical approaches, we envisage that specifically blocking Gal1 in the tumor microenvironment (e.g. using an anti-Gal1 neutralizing mAb) (32), will be successful alone or in combination with other standard treatments to counteract breast cancer-induced immunosuppression, to restrain tumor growth and to prevent lung metastasis.

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LEGENDS TO FIGURES

FIGURE 1. Gal1 expression in breast cancer. (A) Immunohistochemistry of human breast tumors (n=55) histologically classified according to the Scarff-Bloom-Richardson grading system, Grade I (n=16), Grade II (n=24) and Grade III (n=15) and benign mammary hyperplasia (n=7). Tissue sections were stained with a polyclonal anti-Gal1 Ab or H&E. Representative micrographs are shown. (B) Percentage of Gal1-positive cells in at least 10 fields (200x). **P < 0.01 Grade I vs. II and ***P < 0.001 Grade I vs III, Kruskal-Wallis and Dunn’s multiple comparison test. (C) Immunoblotting of Gal1 and Actin in human (T47D, MCF-7 and MDA-MB-231) and mouse (4T1 and C4HD) breast cancer cells lines and mouse normal breast tissue (MNB). A representative experiment of a total of four is shown. (D) Representative micrographs of mouse 4T1 tumors stained for Gal1 (40X and 100X).

FIGURE 2. Targeting Gal1 inhibits tumor growth and prevents lung metastasis in breast cancer. (A,B) Immunoblot of Gal1 (A,B) and Gal3 (B) in 4T1 cells transduced with retroviral vectors expressing Gal1 shRNA or scrambled (Scr) shRNA. Results are representative of five independent experiments. (C, D) Detection of Gal1 secretion by 4T1 cells transduced with Gal1 or Scr shRNA by immunoblot (C) or ELISA (D). Equal loading was checked using Ponceau S staining. Data are representative (C) or are the mean ± S.E.M. (D) of three experiments. (E) Kinetics of tumor growth in BALB/c mice inoculated in the abdominal mammary gland with 15000 KD or Scr 4T1 cells. Results are the mean ± S.E.M of four experiments. (F) In vitro cell proliferation by MTS assay and clonogenic assay (n=5). Data are the mean ± S.E.M (left and middle) or are representative (right) of three experiments. (G) Number of clonogenic lung metastasis. Results are the mean ± S.E.M (left) or are representative (right) of four experiments. (E, G) **P < 0.01, One-way Anova and Tukey
multiple comparisons test. (H) Number of macroscopic metastatic foci in the lung. Results are the mean ± S.E.M (left) or are representative (right) of four experiments with n=3 mice per group. *P < 0.05; unpaired t test. Magnification: 5x. (I) Immunohistochemistry of Gal1 in lung metastasis. Data are representative of four experiments with n=3 mice per group. (J) In vitro invasion assay. 4T1 cells were seeded in Matrigel (8 µm-pore inserts) and 24 h later stained and counted in the outer membrane. Data are the mean ± SEM of three experiments.

FIGURE 3. Targeting Gal1 prevents tumor-associated immunosuppression and T_reg cell expansion. (A-D) Frequency of CD4^+CD25^+Foxp3^+ T_reg cells in the spleen, lymph nodes, primary tumor and lungs of mice bearing WT or Gal1 KD 4T1 tumors. Results are representative of five independent experiments with n=3 mice per group. *P < 0.05. **P < 0.01. One-way Anova and Tukey multiple comparisons test. (E) Immunohistochemistry of FoxP3 and Gal1 in tumor-draining lymph nodes (TDLN). Data are representative of three experiments (Magnification 40x). (F) In vitro differentiation of T_reg cells in the absence or presence of TGF-β and conditioned medium (CM) from Gal1 KD or WT 4T1 cells. Dot plots depict the percentage of CD4^+CD25^+FoxP3^+ cells within the CD4-gated T cell population. Data are representative (left) or are the mean ± SEM (right) of three independent experiments. *P < 0.05; one-way Anova. (G, H) ELISA for IL-5, IL-10 and IFN-γ (G) and proliferation (H) of lymphocytes purified from the spleen or TDLN from mice bearing Gal1 KD or WT tumors and cultured for 72 h in the presence or absence of anti-CD3 and anti-CD28 mAb. The ratio of IL-10 and IFN-γ (G, right) is calculated as a measurement of Th2 polarization. Data are the mean ± SEM of three experiments.*P < 0.05, one-way Anova and Tukey multiple comparisons test.

FIGURE 4. Breast cancer-derived Gal1 promotes systemic immunosuppression. (A-D) Mice (n=5) were simultaneously inoculated with 15000 KD 4T1 cells in the right flank and with 15000 WT
(WT/KD) or 4T1 KD cells (KD/KD) in the left flank. (A) Kinetics of tumor growth in the right flank. Results are the mean ± S.E.M of three experiments. ***P< 0.001; Student’s t-test. (B) Number of lung metastasis foci. Data are the mean ± S.E.M (left) or are representative (right) of three experiments. Magnification: 5x. *P <0.05; Unpaired t test. (C) T-cell proliferation in TDNL from different mice groups. Proliferation Index is defined as the ratio between proliferation of antigen-specific (anti-CD3 + anti-CD28 + 4T1 lysate) /non-specific (anti-CD3 + anti-CD28). Data are the mean ± S.E.M. of three experiments. **P<0.01; One-way Anova and Tukey multiple comparisons tests. (D) Flow cytometry of CD25+Foxp3+ Treg cells within the CD4-gated population in TDNL from different mice groups. Data are representative (left) or are the mean ± S.E.M. (right) of three experiments. *P <0.05; one-way Anova and Bonferroni multiple comparison tests. The corresponding tumor drained by the collected lymph node is shown in parenthesis (Kd or wt). (E) Growth of B16 tumors in BALB/c mice bearing WT 4T1 (left) or Gal1 KD (middle) tumor. As control B16 tumors inoculated in C57BL/6 mice are shown (right). Each line represents B16 tumor growth in an individual mouse. A representative set of tumor growth curves out of three independent experiments is shown.

FIGURE 5: Targeting breast cancer-derived Gal1 impairs Treg suppressive activity and LAT expression. Mice bearing WT or Gal1 KD tumors (n=5 per group) were sacrificed and primary tumors, spleen, lungs and TDNL were excised. (A) Suppression assay. CD25+CD4+ Tresp cells were sorted and co-cultured with CD4+CD25+ FR4+ Treg cells isolated from TDNL at the indicated ratios. Data are the mean ± S.E.M. of three experiments. **P <0.01; one-way Anova. (B, C) Real time qRT-PCR of LAT expression relative to GAPDH in CD4+ T cells sorted from lungs, primary tumor and spleen (B) or in Treg cells sorted from lung metastasis.(C). Data the mean ± S.E.M of three experiments. *P <0.05. (D, E) Immunoblot of LAT and FoxP3 in Treg and non-Treg cells sorted from
TDLN (D) or differentiated in vitro in the presence of TGF-β and CM (1:10 or 1:50) of 4T1 WT or Gal1 KD cells (E). Data are the representative (D, upper panel; E, left panel) or are the mean ± SEM (D, lower panel; E, right panel) of three experiments. *P <0.05; one-way Anova. (F,G) Adoptive transfer of sorted T_{reg} cells isolated from TDLN (WT or KD) to BALB/c mice previously inoculated with a KD or a WT tumor (n=4). Tumor growth (F) and metastasis (G) are shown. Data are the mean ± S.E.M. of three experiments * P<0.05. Unpaired t test.
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Tomas Dalotto-Moreno, Diego O Croci, Juan P Cerliani, et al.

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