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Role of Galectin-3 in Mast Cell Functions: Galectin-3-Deficient Mast Cells Exhibit Impaired Mediator Release and Defective JNK Expression

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Galectin-3 is a member of the β-galactoside-binding animal lectin family expressed in various cell types, including mast cells. To determine the role of galectin-3 in the function of mast cells, we studied bone marrow-derived mast cells (BMMC) from wild-type (gal3+/+) and galectin-3-deficient (gal3−/−) mice. Cells from the two genotypes showed comparable expression of IgE receptor and c-Kit. However, upon activation by FcεRI cross-linkage, gal3−/− BMMC secreted a significantly lower amount of histamine as well as the cytokine IL-4, compared with gal3+/+ BMMC. In addition, we found significantly reduced passive cutaneous anaphylaxis reactions in gal3−/− mice compared with gal3+/+ mice. These results indicate that there is a defect in the response of mast cells in gal3−/− mice. Unexpectedly, we found that gal3−/− BMMC contained a dramatically lower basal level of JNK1 protein compared with gal3+/+ BMMC, which is probably responsible for the lower IL-4 production. The decreased JNK1 level in gal3−/− BMMC is accompanied by a lower JNK1 mRNA level, suggesting that galectin-3 regulates the transcription of the JNK gene or processing of its RNA. All together, these results point to an important role of galectin-3 in mast cell biology. The Journal of Immunology, 2006, 177: 4991–4997.
proinflammatory and immunoregulatory properties (20, 21). In the present study, we have compared the biological responses of mast cells from wild-type (gal3+/+) and galectin-3-deficient (gal3−/−) mice, both in vitro and in vivo, and obtained evidence for the significant involvement of galectin-3 in the mast cell response.

Materials and Methods

Mice
gal3−/− mice were generated as described previously (11) and backcrossed to C57BL/6 for nine generations. Experiments with mice were approved by the Institutional Animal Care and Use Committee of the University of California-Davis (Sacramento, CA).

Preparation of bone marrow-derived mast cells (BMMC), expansion of mast cells from peritoneal cavity, and generation of embryonic fibroblasts
BMMC were prepared as described from bone marrow cultures in BMMC medium (RPMI 1640, 2 mM glutamine, nonessential amino acids, and 55 μM 2-ME supplemented with WEHI-3-conditioned medium) (22, 23) and 4- to 6-wk-old cultures were used for experiments. For some experiments, 3-wk-old cultures were further incubated in the presence of 100 ng/ml mouse recombinant stem cell factor (rSCF; provided by Pharmaceutical Technologies) for 4- to 6-wk-old cultures were used for experiments. For some experiments, IgE-sensitized BMMC were resuspended in 50 μl of culture medium and mixed with 50 μl of Ca2+ and Mg2+ releasing dye (final concentration of Fluoro-4: 1 μM, Fura Red: 2 μM/ml, probenecid: 25 mM, and Pluronic F-127: 0.02%) in Tyrode buffer for 15 min at 37°C. The mixtures were incubated at room temperature for 15 min. The cells were then stimulated with 100 ng/ml mouse monoclonal anti-DNP IgE (Sigma-Aldrich) for 45 min at 37°C. The determination of the JNK activity of the cell lysates in vitro was performed using GST-c-Jun (1–79) as the substrate, as described (29).

Measurement of FcεRI and c-Kit expression
Expression of FcεRI on BMMC was determined by flow cytometry. A total of 107 BMMC were treated with 10 μg of mouse monoclonal anti-DNP IgE, H1 DNP-e-26.82 (25) at 4°C for 40 min, followed by staining with FITC-conjugated anti-IgE Ab (BD Pharmingen). Expression of c-Kit was assessed by staining the cells with PE-conjugated anti-c-Kit Ab (BD Pharmingen). Cells were analyzed by using a FACSCalibur (BD Biosciences).

Activation of BMMC
1) Measurement of histamine release. Mediator release from BMMC induced by FcεRI cross-linkage was performed as described (26). BMMC were sensitized overnight with 500 ng/ml mouse monoclonal anti-DNP IgE, H1 DNP-e-26.82 (25). Cells were resuspended and then stimulated with 0–100 ng/ml DNP-BSA in Tyrode buffer for 45 min at 37°C. Measurement of cytokine release and kinases. BMMC were activated as described above, except that activation was performed in BMMC medium, and for various periods (0.5–4 h). In some experiments, IgE-mediated activation was accomplished by incubating the cells in tissue culture wells coated with IgE. Briefly, 96-well plates were coated with 10 μg/ml anti-DNP IgE in PBS at 37°C for 1 h. A total of 105 BMMC in 100 μl were added into each well. The plates were spun and incubated at 37°C for 4 h. In experiments to measure histamine and cytokines, the BMMC were harvested with 0.1% gelatin. The control (contralateral) site was injected with 15 μl of diluent only. After 3–4 h, mice were challenged with 200 μl of 1 mg/ml DNP-BSA along with 1% Evans blue in saline i.v. through the tail vein.

Immunoblot analysis
Immunoblot analyses of galectin-3 (28) and kinases (29) were performed as described. The primary Abs used were: JNK and JNK1/2, mouse mAb recognizing, respectively, JNK1 only and both JNK1 and JNK2 (BD Pharmingen); ERK1/2 and p38, respective mouse mAb (Santa Cruz Biotechnology); galectin-3, rabbit polyclonal Ab to human galectin-3 (28); tumor necrosis factor (TNF)-α, a mouse mAb (Sigma-Aldrich); phosphorylated c-Jun (p-c-Jun), rabbit anti-phospho-c-Jun Ab (Cell Signaling Technology); and rabbit Ab (Santa Cruz Biotechnology). Secondary Abs used were: HRP-conjugated goat anti-mouse IgG and HRP-conjugated goat anti-rabbit IgG (Chemicon International).

In vitro kinase assay
IgE-sensitized BMMC were stimulated with 30 ng/ml DNP-BSA in Tyrode buffer for indicated time periods at 37°C. The determinations of the JNK activity of the cell lysates in vitro was performed using GST-c-Jun (1–79) as the substrate, as described (29).

Measurement of protein kinase C (PKC) activation associated with granule exocytosis
IgE-sensitized BMMC were stimulated with 30 ng/ml DNP-BSA for indicated time periods. The cells were extracted with lysis buffer (1% Nonidet P-40, 25 mM Tris-HCl, 150 mM NaCl, 2 mM EDTA, 100 mM NaVO4, and 1000× diluted protease inhibitor mixture (Sigma-Aldrich)) on ice for 30 min. A total of 100 μg of total lysate protein were mixed with 1 μM of anti-PKCβII Ab (Santa Cruz Biotechnology) followed by 20 μl of protein G-Sepharose 4B beads (Zymed Laboratories). After the beads were washed with lysis buffer, the bound proteins were eluted and analyzed by immunoblotting using anti-p-Pan-PKC (Cell Signaling Technology) and anti-PKCβII. The relative density of the p-PKCβII over total PKCβII protein bands was analyzed by using ImageJ version 1.36 (W. S. Rasband, National Institutes of Health, Bethesda, MD; http://rsb.info.nih.gov/ij/, 1997–2006).

Measurement of calcium influx
IgE-sensitized BMMC were resuspended in 50 μl of culture medium and mixed with 50 μl of Ca2+ detecting dye (final concentration of Fluoro-4: 1 μg/ml, Fura Red: 2 μg/ml, probenecid: 25 mM, and Pluronic F-127: 0.02%) in Tyrode buffer. The mixtures were incubated at room temperature for 15 min. The cells were then stimulated with 30 ng/ml or 1 μg/ml DNP-BSA and analyzed on a Coulter EPICS XL flow cytometer (Coulter). List mode files were analyzed using FlowJo (Tree Star). Fura Red, Fluoro-4, and Pluronic F-127 are all from Molecular Probes. Probenecid was from Alfa Aesar.

Polymerase chain reactions
First, quantitation of JNK mRNA by RT-PCR was performed. Total RNA from resting and activated BMMC was isolated using TRI reagent (Molecular Research Center) following the manufacturer’s protocol. To synthesize cDNA from total RNA was used to synthesize cDNA by using Omniscript reverse transcriptase kit (Qiagen) and reverse primers (ccgagatcataagg). As a control, G3PDH cDNA was amplified in the same samples. The PCR products were visualized by agarose gel electrophoresis.

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Gal3 is known to be induced by IgE. We treated the cells with increasing concentrations of IgE and then measured the levels of cell surface FcεRI. gal3−/− and gal3+/+ BMMC displayed comparable amounts of FcεRI after treatment with various doses of IgE (data not shown). We also determined the levels of another marker of mast cell differentiation, c-Kit, which is the receptor for SCF and plays a key role in mast cell proliferation and differentiation. The expression of c-Kit in the two genotypes was comparable (Fig. 1C).

gal3−/− BMMC exhibit diminished cytokine production

Besides degranulation, mast cell activation also leads to signaling events resulting in production of various cytokines, including IL-4. gal3−/− and gal3+/+ BMMC were activated by FcεRI cross-linkage with various doses of DNP-BSA and IL-4 in the culture supernatants was quantitated by ELISA. As shown in Fig. 2A, gal3−/− BMMC produced greater amounts of IL-4 than gal3+/+ BMMC at all of the doses of DNP-BSA used. The time course of the response of the two genotypes to DNP-BSA was also compared and the reduced IL-4 release from gal3−/− BMMC was apparent at all the time points tested (Fig. 2B). Thus, the reduced response of gal3−/− BMMC was not due to slower kinetics.
The above experiments required the sensitization of the cells with IgE overnight and there existed a possibility that the defect observed for gal3\(^{-/-}\) BMMC was due to an altered response in the sensitization phase. We performed experiments in which BMMC were cultured in plastic wells coated with anti-DNP IgE, and thus activated directly, as cell surface FcERI was cross-linked by solid phase IgE. As shown in Fig. 2C, IL-4 production was significantly lower in gal3\(^{-/-}\) BMMC compared with gal3\(^{+/+}\) BMMC.

gal3\(^{-/-}\) mice exhibit reduced PCA reactions

To determine whether galectin-3 deficiency results in a defective mast cell response in vivo, we compared the PCA reactions in gal3\(^{+/+}\) and gal3\(^{-/-}\) mice. Mice were given serial dilutions of mouse monoclonal anti-DNP IgE intradermally and then challenged with the multivalent Ag DNP-BSA i.v. The cutaneous reaction was gauged by the extravasation of the i.v. injected dye at the sensitized sites. As shown in Fig. 3, gal3\(^{-/-}\) mice showed significantly lower cutaneous reactions compared with gal3\(^{+/+}\) mice. Mast cell numbers in the skin were not significantly different between the two genotypes (data not shown).

gal3\(^{-/-}\) BMMC are defective in the expression of JNK1 protein

It has been shown that recombinant galectin-3 can induce mediator release from mast cells, when added to cultures of these cells (17). Thus, one possible cause for the difference between gal3\(^{+/+}\) and gal3\(^{-/-}\) BMMC in response to activation is that galectin-3 released by the cells might activate the neighboring cells in a paracrine fashion. We performed the activation of BMMC in the presence of lactose, which is known to inhibit the binding of galectin-3 to glycoconjugates (17, 32). The amount of IL-4 released was not affected by lactose in both genotypes of mast cells (data not shown).

Galectin-3 has been shown to be present inside mast cells (16) and have a number of different intracellular functions in various other cell types (reviewed in Ref. 8). Thus, galectin-3 may regulate the mast cell response through an intracellular mechanism(s). Because our results show that galectin-3 is involved in IL-4 production, we focused on the signal transduction pathway leading to transcriptional activation of the cytokine gene in mast cells. We found that gal3\(^{+/+}\) and gal3\(^{-/-}\) BMMC did not differ in the phosphorylation of ERK1/2 and MEK (data not shown). However, when we analyzed activation of JNK, we found a strikingly diminished basal protein level of the 46-kDa isoform of JNK1 in gal3\(^{-/-}\) BMMC (Fig. 4A). There is no difference in the 55-kDa isoform of this kinase (Fig. 4A). When the same membrane was reprobed with Ab that recognizes both JNK1 and JNK2, there was no appreciable difference in the signals from mast cells between the two genotypes. The results suggest that the Ab may detect primarily JNK2 and thus the difference in JNK1 was masked.

The decreased JNK1 protein level in gal3\(^{-/-}\) BMMC is not due to a global defect in protein expression in these cells. The expression levels of other kinases P38 and ERK1/2 were comparable between the two genotypes (Fig. 4B). In addition, the baseline expression levels of β and γ subunits of FcERI and various other upstream tyrosine and serine-threonine kinases, namely Lyn, Syk, Btk, Emt, PLC-γ1, Grb 2, HS1, PKCα, PKCβ1, were also comparable between the two genotypes, as determined by immunoblot analysis (data not shown).

JNK has been shown to be inducible in T cells, when activated by PMA or anti-CD3 Ab (33). Therefore, we determined whether JNK1 is also inducible in mast cells and whether the galectin-3 affects its induction. We activated mast cells by cross-linking FcERI for 12 and 24 h and then analyzed the JNK1 level by immunoblotting. We found that JNK1 was inducible in mast cells in both gal3\(^{+/+}\) and gal3\(^{-/-}\) BMMC, but even after prolonged activation, the JNK1 protein content in gal3\(^{-/-}\) BMMC was substantially lower than that in gal3\(^{+/+}\) BMMC (Fig. 4C).

BMMC are believed to show the phenotype of mature mast cells if grown in the presence of SCF (34). We measured the JNK1 level in 3-wk-old BMMC that were further cultured in the presence of SCF for 2 wk and still noted defective expression in gal3\(^{-/-}\) BMMC (Fig. 4D). We also measured the JNK1 level in mast cells...
originating from the peritoneal cavity and expanded in the presence of SCF. As shown in Fig. 4E, the association between low JNK1 expression and galectin-3 deficiency is retained. To determine whether the defective JNK1 expression in gal3−/− mice is cell type specific, we tested the JNK1 levels in other cell types from gal3+/+ and gal3−/− mice. We did not see any difference in JNK1 levels in embryonic fibroblasts (Fig. 4F), as well as in resting and activated macrophages and lymphocytes (data not shown).

gal3−/− BMMC are defective in activation of c-Jun
Consistent with the defective JNK1 expression, phosphorylation of c-Jun was significantly lower in gal3−/− BMMC compared with gal3+/+ BMMC that were activated by FcεRI cross-linkage (Fig. 5A). In addition, we precipitated JNK1 in the cell lysates and quantitated the c-Jun kinase activity in the precipitates by an in vitro kinase assay. As shown in Fig. 5B, immunoprecipitates from gal3−/− BMMC had significantly reduced ability to phosphorylate c-Jun compared with gal3+/+ BMMC. Comparison of the relative amounts of phosphorylated c-Jun with those of JNK1 between the two genotypes showed that JNK1 in gal3−/− BMMC had lower kinase activity compared with that in gal3+/+ BMMC.

gal3−/− BMMC have reduced IL-4 mRNA and JNK mRNA
Because IL-4 production is controlled by JNK at the transcription level, our results suggested that the decreased IL-4 production in gal3−/− BMMC may be due to a reduced level of transcription of this cytokine. By using real-time PCR, we compared the IL-4 mRNA levels in gal3+/+ and gal3−/− BMMC that were activated by FcεRI cross-linkage. As shown in Fig. 6A, the level was significantly lower in gal3−/− BMMC than gal3+/+ BMMC.

As a first step in elucidating the mechanism by which JNK expression is regulated by galectin-3, we determined whether transcriptional regulation is involved. We compared the mRNA levels of JNK1 in gal3+/+ and gal3−/− BMMC by RT-PCR. The results showed that the basal level of JNK1 mRNA was lower in gal3−/− BMMC compared with gal3+/+ BMMC (Fig. 6B). There was a rapid induction of JNK1 mRNA in both genotypes upon activation by FcεRI cross-linkage. However, the level in gal3−/− BMMC remained considerably lower than that in gal3+/+ BMMC (Fig. 6B).

To determine whether galectin-3 controls JNK1 gene transcription, we tested the effect of galectin-3 on the activation of JNK promoter by a reporter assay. We did not detect induction of JNK promoter by galectin-3 in gal3−/− BMMC cotransfected with JNK promoter-reporter construct and galectin-3 (data not shown).

Suppression of IL-4 production in BMMC by a JNK inhibitor
Although JNK is known to mediate cytokine production in T cells, its role in IL-4 production in mast cells has not been demonstrated. To confirm that defective JNK1 synthesis and activation as seen in gal3−/− mast cells can result in reduced IL-4 production, we tested whether inhibition of JNK1 can suppress IL-4 production. gal3−/+ and gal3−/− BMMC were activated in the presence of a serially diluted JNK inhibitor, SP600125 (35). As shown in Fig. 7, IL-4 release in both gal3−/+ and gal3−/− BMMC was inhibited by this drug in a dose-dependent fashion.

gal3−/+ and gal3−/− BMMC do not differ significantly in signaling pathways linked to secretory granule exocytosis
Because JNK1 is not known to be involved in the signaling events associated with mast cell granule exocytosis, we conducted experiments to determine how galectin-3 contributes to this process. Galectin-3 does not appear to regulate some upstream events, such as activation of receptor-associated tyrosine kinases, because tyrosine phosphorylation of both Lyn and Syk were comparable in
Discussion

The functions of galectin-3 have previously been studied mainly by treating various cells with exogenously added recombinant protein, and by this approach, galectin-3 has been shown to be able to activate various cell types, including mast cells (17). The availability of genetically engineered galectin-3-deficient mice has made it possible to study the role of endogenous galectin-3 in various cell types. Our results show the involvement of galectin-3 in the FcεRI-mediated mast cell response. BMMC from gal3−/− mice exhibited significantly reduced degranulation (i.e., histamine release) and lower cytokine (IL-4) production upon FcεRI cross-linkage. Importantly, gal3−/− mice exhibit a significantly diminished cutaneous mast cell response in vivo, as demonstrated by PCA reactions.

Like all other members of the galectin family, galectin-3 does not contain a classical signal sequence. Nevertheless, it can be secreted from various cell types (5), including mouse macrophage cell lines stimulated with a calcium ionophore (36). However, the possibility that galectin-3 released by mast cells in turn activates neighboring cells in a paracrine fashion, through binding to cell surface glycoconjugates, is excluded by the following experimental results. We activated gal3−/− BMMC by FcεRI cross-linkage in the presence of lactose, which would bind to extracellular galectin-3 and inhibit its activity, or with another disaccharide, sucrose, which does not bind to the lectin. We found that IL-4 production was not affected by the presence of either sugar (data not shown). These results strongly suggest the involvement of galectin-3 in mast cell signaling through an intracellular mechanism.

Based on our results, some potential causes of lower degranulation and cytokine production in gal3−/− BMMC can be excluded. First, the deficiency is not due to a reduction in the number of FcεRI on the cells. Second, it is not due to lack of differentiation of these cells, as we found comparable levels of cell surface c-Kit (Fig. 1C) and mRNA of a mast cell-specific protease, MCP-5 (data not shown) in cells from the two genotypes. Third, galectin-3 does not appear to regulate some upstream events, such as activation of receptor-associated tyrosine kinases, because tyrosine phosphorylation of both Lyn and Syk were comparable in gal3−/− and gal3−/− BMMC activated by FcεRI cross-linkage (data not shown). Our present study provides a significant mechanistic insight into the regulation of mast cell cytokine production by galectin-3 and that is the involvement of this lectin in regulation of JNK1 expression. JNK1 is known to play an important role in the production of cytokines from T cells by activating the transcription factor c-Jun, which is in turn involved in transcription of various cytokines (37).

Thus, the reduced cytokine production in gal3−/− BMMC is likely due to the lower JNK1 level. It is to be noted that only one of the two isoforms of JNK1 is affected, and this could explain a partial reduction in IL-4 production as the other isoform is likely to regulate the production of this cytokine also.

The basis for galectin-3’s regulation of JNK1 expression remains to be elucidated. Our finding that gal3−/− BMMC contains significantly lower JNK1 transcript suggests that galectin-3 regulates JNK1 transcription. Galectin-3 has been shown to interact with a thyroid transcription factor, TTF, and potentiate the activity of this factor (38). It is conceivable that galectin-3 regulates the transcription factor involved in the expression of JNK1. However, our experiments with a reporter assay did not support the control of JNK promoter activity by galectin-3 (data not shown). The finding that only one isoform is affected is unusual. Because these isoforms are products of alternative splicing, the intriguing possibility exists that galectin-3 regulates differential splicing of JNK pre-mRNA. In this regard, it is interesting to note that galectin-3, as well as galectin-1, has been shown to be active in inducing pre-mRNA splicing in vitro (39).

How galectin-3 regulates degranulation needs to be considered, since this process is not known to be dependent on JNK1. We studied a number of signaling events and molecules known to contribute to secretory granule exocytosis, including calcium influx, phosphorylation of PLCγ1, and the adaptor molecule LAT, and activation of PKCβ and did not notice significant alterations in gal3−/− BMMC. We cannot exclude the possibility that galectin-3...
regulates activation of the soluble N-ethylmaleimide-sensitive factor attachment receptor complex that is involved in the membrane fusion during degranulation (40). Galectin-3 has recently been shown to be present in the lumen of intracellular vesicles containing glycoproteins destined to the apical site of epithelial cells (41). A model has been proposed in which galectin-3 is responsible for clustering these apical glycoproteins and facilitating the generation of apical vesicles. Because galectin-3 is present in secretory granules in mast cells (16), an intriguing possibility exists that galectin-3 is involved in clustering of glycoproteins contained in the granules and thus facilitating the targeting of these granules to the plasma membrane before exocytosis.

Our results strengthen the notion that the galectins can function intracellularly. Such functions are unexpected from the lectin properties, but are consistent with their intracellular localization (42). These functions likely involve interactions with intracellular proteins, which could be dependent or independent of carbohydrates. Saccharides, especially the O-linked varieties, do exist in the cytoplasm and may potentially be ligands of cytosolic galectins. However, there is evidence that galectin-3 interacts with proteins that are not glycoproteins, suggesting the involvement of carbohydrate-independent protein-protein interactions (reviewed in Ref. 8).

In conclusion, our studies have established an important role for galectin-3 in the mast cell response. In view of the well-established significance of mast cells in allergic inflammation, our studies suggest that galectin-3 could be a potential therapeutic target for controlling allergic disorders.

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Disclosures

The authors have no financial conflict of interest.

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