

Luminex
complexity simplified.



**Simple, Compact, and
Affordable Cell Analysis.**
Muse® Cell Analyzer.

LEARN MORE >



Galectin-9 Induces Apoptosis Through the Calcium-Calpain-Caspase-1 Pathway

Yumiko Kashio, Kazuhiro Nakamura, Mohammad J. Abedin, Masako Seki, Nozomu Nishi, Naoko Yoshida, Takanori Nakamura and Mitsuomi Hirashima

This information is current as of October 17, 2019.

J Immunol 2003; 170:3631-3636; ;
doi: 10.4049/jimmunol.170.7.3631
<http://www.jimmunol.org/content/170/7/3631>

References This article **cites 58 articles**, 26 of which you can access for free at:
<http://www.jimmunol.org/content/170/7/3631.full#ref-list-1>

Why *The JI*? Submit online.

- **Rapid Reviews! 30 days*** from submission to initial decision
- **No Triage!** Every submission reviewed by practicing scientists
- **Fast Publication!** 4 weeks from acceptance to publication

**average*

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>

The Journal of Immunology is published twice each month by
The American Association of Immunologists, Inc.,
1451 Rockville Pike, Suite 650, Rockville, MD 20852
Copyright © 2003 by The American Association of
Immunologists All rights reserved.
Print ISSN: 0022-1767 Online ISSN: 1550-6606.



Galectin-9 Induces Apoptosis Through the Calcium-Calpain-Caspase-1 Pathway¹

Yumiko Kashio,* Kazuhiro Nakamura,* Mohammad J. Abedin,* Masako Seki,*[‡]
Nozomu Nishi,[†] Naoko Yoshida,*[‡] Takanori Nakamura,[†] and Mitsuomi Hirashima^{2*§}

Galectin-9 (Gal-9) induced the apoptosis of not only T cell lines but also of other types of cell lines in a dose- and time-dependent manner. The apoptosis was suppressed by lactose, but not by sucrose, indicating that β -galactoside binding is essential for Gal-9-induced apoptosis. Moreover, Gal-9 required at least 60 min of Gal-9 binding and possibly de novo protein synthesis to mediate the apoptosis. We also assessed the apoptosis of peripheral blood T cells by Gal-9. Apoptosis was induced in both activated CD4⁺ and CD8⁺ T cells, but the former were more susceptible than the latter. A pan-caspase inhibitor (Z-VAD-FMK) inhibited Gal-9-induced apoptosis. Furthermore, a caspase-1 inhibitor (Z-YVAD-FMK), but not others such as Z-IETD-FMK (caspase-8 inhibitor), Z-LEHD-FMK (caspase-9 inhibitor), and Z-AEVD-FMK (caspase-10 inhibitor), inhibited Gal-9-induced apoptosis. We also found that a calpain inhibitor (Z-LLY-FMK) suppresses Gal-9-induced apoptosis, that Gal-9 induces calcium (Ca²⁺) influx, and that either the intracellular Ca²⁺ chelator BAPTA-AM or an inositol trisphosphate inhibitor 2-aminoethoxydiphenyl borate inhibits Gal-9-induced apoptosis. These results suggest that Gal-9 induces apoptosis via the Ca²⁺-calpain-caspase-1 pathway, and that Gal-9 plays a role in immunomodulation of T cell-mediated immune responses. *The Journal of Immunology*, 2003, 170: 3631–3636.

Galectin-9 (Gal-9)³ is a β -galactoside binding lectin that belongs to a growing animal lectin family of galectins (1, 2). We cloned ecalectin as a T cell-derived eosinophil chemoattractant (3) and showed that Gal-9 is identical with ecalectin (1). Gal-9 has N- and C-terminal carbohydrate recognition domains (4, 5) that are connected by a linker peptide (2, 6–8).

Galectins modulate a variety of biological functions, such as cell activation, proliferation, adhesion, and apoptosis (9–11). Like other galectins, Gal-9 exhibits various biological functions, such as cell aggregation and chemoattraction of eosinophils, as well as apoptosis of murine thymocytes and T cells, and human melanoma cells (3, 12–15).

Apoptosis is induced by several stimuli, including galectins, and apoptosis pathways have been intensively studied. Accordingly, several pathways have been proposed. Although the activation of caspase-3 and -7 is essentially required for all pathways, activation of a different caspase is involved upstream. For example, caspase-1 (16–18), caspase-8 (19, 20), caspase-9 (21), and caspase-10 (22, 23) are required for apoptosis mediated through association with glucocorticoid (GC), Fas/TNF, mitochondria or perforin, respectively. Gal-1 induces the apoptosis of T cells (24), thymocytes

(25), and prostate cancer (26) through the down-regulation of Bcl-2 (27) and caspase activation. Gal-1 does not require an increase in intracellular Ca²⁺ to induce apoptosis (28). Gal-7 is a proapoptotic protein that functions intracellularly upstream of c-Jun N-terminal kinase activation and cytochrome *c* release (29, 30). Although Gal-9 can trigger the apoptosis of murine thymocytes and melanoma (12, 15), the pathway has not been clarified. The purpose of the present study was to show that human Gal-9 induces the apoptosis of T cells via the Ca²⁺-calpain-caspase-1 pathway.

Materials and Methods

Cell culture

MOLT-4 (T cells), Jurkat (T cells), BALL-1 (B cells), THP-1 (monocytes), and HL-60 (myelocytes) obtained from American Type Culture Collection (Manassas, VA) were maintained in RPMI 1640 medium (Sigma-Aldrich, St. Louis, MO) supplemented with 10% FCS at 37°C in 5% CO₂. The activity of Gal-9 was inhibited by adding 30 mM lactose to the culture medium. Sucrose at the same concentration served as the control.

Expression and purification of recombinant Gal-9 (rGal-9)

Recombinant Gal-9 was expressed and purified as previously described (31, 32). In brief, *Escherichia coli* BL-21 cells containing a Gal-9 expression plasmid were cultured in Luria-Bertoni medium (Life Technologies, Gaithersburg, MD) containing 100 μ g/ml ampicillin. Isopropyl- β -D-thiogalactopyranoside (Wako, Osaka, Japan) was added to induce the expression of fusion proteins. Adsorbed protein was eluted from *E. coli* extract by lactose agarose affinity chromatography (Seikagaku, Tokyo, Japan) using 200 mM lactose. Fractions were collected and analyzed by SDS-PAGE after staining with Coomassie brilliant blue R 250. Fractions containing rGal-9 were pooled and dialyzed against PBS containing 0.1 mM DTT.

Apoptosis assay

Cultured cells were incubated with rGal-9 for 24 h, then pelleted cells sedimented by centrifugation were resuspended in 300 μ l of PBS and 700 μ l of 100% ethanol. The cells were washed with PBS and incubated with 50 μ g/ml ribonuclease A (Sigma-Aldrich) for 30 min at 37°C, then with 50 μ g/ml of propidium iodide (PI; Sigma-Aldrich) for 10 min. Stained cells were analyzed by flow cytometry (33, 34).

Departments of *Immunology and Immunopathology, and [†]Endocrinology, Kagawa Medical University, Ikenobe, Miki-cho, Kita-gun, Kagawa, Japan; and [‡]Research Division, GalPharma Co. Ltd., NEXT-Kagawa, Hayashi-cho, Takamatsu, Kagawa, Japan

Received for publication September 5, 2002. Accepted for publication February 10, 2003.

The costs of publication of this article were defrayed in part by the payment of page charges. This article must therefore be hereby marked *advertisement* in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

¹ This work was supported in partly by a grant from the Ministry of Education, Science, and Culture, Japan.

² Address correspondence and reprint requests to Prof. Mitsuomi Hirashima, Department of Immunology and Immunopathology, Kagawa Medical University, 1750-1 Ikenobe, Miki-cho, Kita-gun, Kagawa 761-0793, Japan. E-mail: mitsuomi@kms.ac.jp

³ Abbreviations used in this paper: Gal-9, galectin-9; 2-APB, 2-aminoethoxydiphenyl borate; DEX, dexamethasone; GC, glucocorticoid; IP₃, inositol trisphosphate; PI, propidium iodide.

The apoptosis assay proceeded using the MEBCYTO apoptosis kit (MBL, Nagoya, Japan) according to the manufacturer's instructions. In brief, cells were washed and resuspended in binding buffer. Annexin V-FITC and PI were added to the cell suspension, and then the mixture was incubated for 15 min in the dark at room temperature. Thereafter, the suspension was analyzed using a flow cytometer (EPICS XL-MCL; Coulter, Miami, FL).

To assess the Gal-9-mediated apoptotic pathway, cells were cultured with cycloheximide (a protein synthesis inhibitor; Sigma-Aldrich) in the presence or the absence of 1 μ M Gal-9 for 24 h to determine whether de novo protein synthesis is required for Gal-9-mediated apoptosis (35).

Cells were incubated with Gal-9 in the presence of 10 μ M Z-VAD-FMK (pan-caspase inhibitor), Z-YVAD-FMK (caspase-1 inhibitor), Z-IETD-FMK (caspase-8 inhibitor), Z-LEHD-FMK (caspase-9 inhibitor), Z-AEVD-FMK (caspase-10 inhibitor), or Z-LLY-FMK (calpain inhibitor; BioVision, Mountain View, CA) to examine the involvement of caspase or calpain in Gal-9-induced apoptosis. Z-FA-FMK (BioVision) served as the control (36, 37).

To clarify the requirement for Ca^{2+} flux in Gal-9-mediated apoptosis, apoptosis was induced by Gal-9 in the presence or the absence of an extracellular Ca^{2+} chelator 4 mM EGTA (Dojindo, Kumamoto, Japan) (38), or cells were also preincubated with either intracellular Ca^{2+} chelator 30 μ M BAPTA-AM (Dojindo) for 10 min (39) or an inositol trisphosphate (IP_3) inhibitor 30 μ M 2-aminoethoxydiphenyl borate (2-APB; Calbiochem, San Diego, CA) for 10 min (40, 41), followed by treatment with 1 μ M Gal-9.

The following proapoptotic reagents were purchased from the indicated suppliers: dexamethasone (DEX; BioVision), anti-Fas Ab (clone CH-11; MBL), TNF- α (Genzyme, Cambridge, MA), C2 ceramide (Sigma-Aldrich), and etoposide (BioVision).

T cell analysis

Twenty-four-well plates were coated with 3 μ g/well anti-CD3 Ab (Immunotech, Marseilles, France). The mononuclear leukocyte fraction was isolated with Histopaque (Sigma-Aldrich). CD4- or CD8-positive T cells were isolated using a CD4-positive selection kit and Dynabeads M-450 CD8 (DynaL Biotech, Oslo, Norway) as previously described by the manufacturer. T cells were activated by incubation on anti-CD3-coated plates for 24 h at 37°C, followed by rGal-9 treatment.

Ca^{2+} mobilization

Cells (1×10^7 /ml) in culture medium (10% FCS and 10 mM HEPES, pH 7.2) were loaded with fluo-3/AM (final concentration, 10 μ M), an intracellular Ca^{2+} indicator (Dojindo) at 37°C for 30 min (42). The cells were washed and resuspended in culture medium. Intracellular Ca^{2+} was measured using a flow cytometer. A stimulus was applied to the cells 1 min after measuring the fluorescence intensity of resting cells, then continuous recording was started again until another stimulus was applied. To assay lactose inhibition, cells were stimulated in the presence of 30 mM lactose, and 30 mM sucrose served as the control (43). A23187 (Ca^{2+} ionophore; final concentration, 5 ng/ml; Wako) served as the positive control.

Results

Induction of apoptosis by Gal-9

We examined whether Gal-9 could induce apoptosis of the cell lines. MOLT-4 was incubated with rGal-9 (1 μ M) for various incubation periods (3, 6, 12, 24, 48, and 72 h) and was stained with PI to differentiate apoptotic cells. Fig. 1A showed that rGal-9 induces the apoptosis of MOLT-4 cells in a time-dependent manner. Apoptosis was significantly, but weakly, induced by 1 μ M Gal-9 at 6 h and strongly induced after 12 h of incubation. Moreover, MOLT-4 cells were incubated with various concentrations of rGal-9 (0.03, 0.1, 0.3, and 1.0 μ M) for 24 h to clarify the dose dependency. Fig. 1B shows that apoptosis was induced in a dose-dependent fashion. At least 0.1 μ M Gal-9 was required for significant induction of apoptosis.

We also examined the proapoptotic activity of Gal-9 by annexin V staining, which detects phosphatidylserine that is externalized during apoptosis. We found that the numbers of apoptotic cells detected with annexin V were increased from 13.2 to 69.1% by 1 μ M Gal-9, confirming that Gal-9 exhibits proapoptotic activity against MOLT-4.

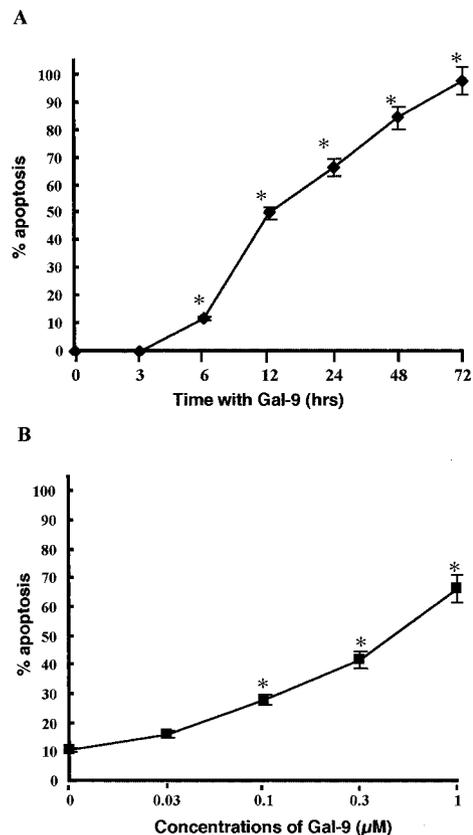


FIGURE 1. Gal-9 induces apoptosis in a time- (A) and dose- (B)-dependent manner. MOLT-4 cells were incubated with 1 μ M rGal-9 for various incubation periods (A). The cells were also incubated with various concentrations of rGal-9 for 24 h (B). The proapoptotic activity of Gal-9 against MOLT-4 was assessed by PI labeling as described. Data are the mean \pm SEM of four experiments. ANOVA was used for statistical analysis. *, $p < 0.05$.

We further examined the minimal time of Gal-9 binding required to induce the apoptosis. Cells were treated with Gal-9 for various periods (0, 15, 30, 60, 120, and 240 min) and were further cultured in the absence of Gal-9 for a total of 24 h, followed by assessment of apoptosis. Fig. 2A showed that Gal-9-mediated apoptosis in MOLT-4 requires at least 60 min of Gal-9 binding to induce detectable Gal-9-mediated apoptosis, although a longer period of incubation is more effective for the induction.

Furthermore, to examine the requirement for synthesis of a Gal-9-inducible factor, cells were exposed for 24 h to various concentrations of cycloheximide (0, 10, 100, and 1000 nM) in the presence or the absence of 1 μ M Gal-9. The results were shown in Fig. 2B. Cycloheximide suppressed Gal-9-induced apoptosis in a dose-dependent manner, suggesting that Gal-9 required de novo protein synthesis to exhibit its proapoptotic activity.

Gal-9 causes apoptosis of various cells

We examined whether such Gal-9 proapoptotic activity is applicable to other cell lines that were cultured with or without 1 μ M rGal-9 for 24 h and assessed for apoptosis. Fig. 3A shows that the apoptosis not only of T cells but also of B cells (BALL-1), monocytes (THP-1), and myelocytes (HL-60) is induced by Gal-9.

Next, we examined the effects of lactose on the ability of Gal-9 to induce apoptosis. Fig. 3A shows that the proapoptotic activity of Gal-9 is almost completely inhibited by 30 mM lactose, but not by sucrose, indicating that β -galactoside binding activity is essentially required for Gal-9-induced apoptosis.

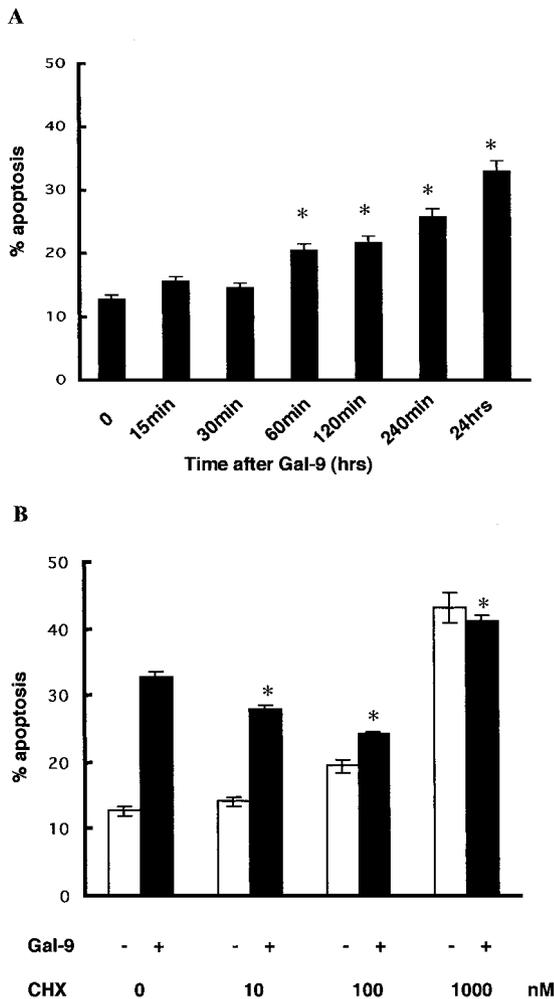


FIGURE 2. Gal-9-mediated apoptosis requires Gal-9 binding (A) and de novo protein synthesis (B). The proapoptotic activity of Gal-9 was assessed as described. Data are represented as the mean \pm SEM of three experiments. *, $p < 0.05$.

We further assessed the Gal-9-induced apoptosis of human peripheral blood T cells separated into CD4⁺ and CD8⁺ T cells and activated with or without anti-CD3 Ab. The cells were then incubated in the presence of 1 μ M rGal-9. Fig. 3B shows that Gal-9 induced more obvious apoptosis in both CD3-activated CD4⁺ and CD8⁺ T cells than in nonactivated CD4⁺ and CD8⁺ T cells. Moreover, we found that CD4⁺ T cells were more susceptible to Gal-9 than CD8⁺ T cells (Fig. 3B).

Caspase inhibition

We examined whether caspase activation is involved in Gal-9-induced apoptosis. MOLT-4 cells were incubated with the pan-caspase inhibitor, Z-VAD-FMK, then with rGal-9. Fig. 4A shows that Gal-9-induced apoptosis was almost completely suppressed by the caspase inhibitor. We also found that apoptosis induced by other stimuli, such as DEX, anti-Fas Ab, TNF- α , and C2 ceramide, was suppressed by the pan-caspase inhibitor (data not shown).

We then investigated other caspase inhibitors for specific upstream caspases, namely, Z-YVAD-FMK for caspase-1, Z-IETD-FMK for caspase-8, Z-LEHD-FMK for caspase-9, and Z-YVAD-FMK for caspase-10. Fig. 4A also shows that only Z-YVAD-FMK (caspase-1 inhibitor) suppressed Gal-9-induced apoptosis, whereas other caspase inhibitors for caspase-8, -9, and -10 did not. We confirmed that caspase-1 and caspase-9 inhibitors suppressed

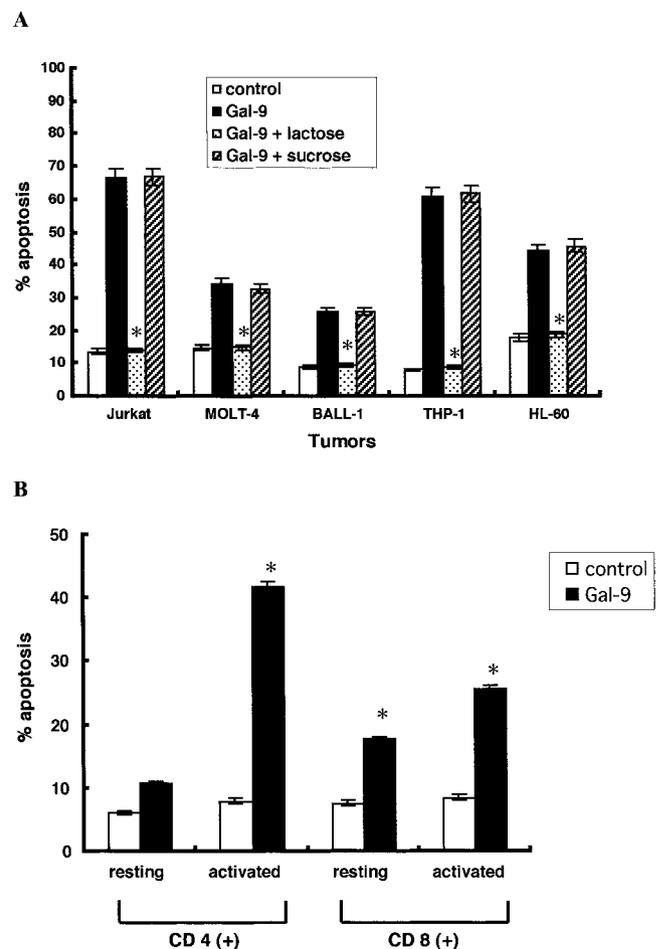


FIGURE 3. Gal-9 induces apoptosis of various cells. Proapoptotic activity of Gal-9 was assessed as described. A, Jurkat, MOLT-4, BALL-1, THP-1, and HL-60 were incubated with or without 30 mM lactose or sucrose, followed by 1 μ M Gal-9, then apoptotic cells were assessed by PI. □, Percentage of apoptosis without Gal-9. B, Separated CD4⁺ or CD8⁺ T cells were activated with anti-CD3 Ab, and proapoptotic activities of Gal-9 were assessed by PI. The percent apoptosis of the cells treated with or without Gal-9 is shown. Data are the mean \pm SEM of three experiments. *, $p < 0.05$.

DEX-mediated apoptosis, that caspase-8 and caspase-10 inhibitors suppressed apoptosis induced by anti-Fas Ab and TNF- α , and that the caspase-9 inhibitor suppressed apoptosis induced by C2 ceramide (data not shown). Fig. 4, B and C, show that both the pan-caspase and caspase-1 inhibitors suppressed Gal-9-induced apoptosis time- and dose-dependently. Such suppression was reproducible in other cell lines (data not shown). The present results suggested that Gal-9 probably induces apoptosis through caspase-1 activation, and that caspase-8, caspase-9, and caspase-10 are not involved in Gal-9-mediated apoptosis.

Ca²⁺-calpain pathway

Since calpain, a Ca²⁺-dependent protease, is required for caspase-1 activation (44, 45), we examined whether calpain-caspase-1 activation is involved in Gal-9-induced apoptosis in MOLT-4. Fig. 5, A and B, show that the calpain inhibitor, Z-LLY-FMK, inhibits Gal-9-induced apoptosis time- and dose-dependently.

We performed Fluo-3 assays to determine whether Gal-9 causes a Ca²⁺ influx in MOLT-4. Fig. 6 shows that a Ca²⁺ influx was generated in MOLT-4 within 10–20 s after adding Gal-9, and that

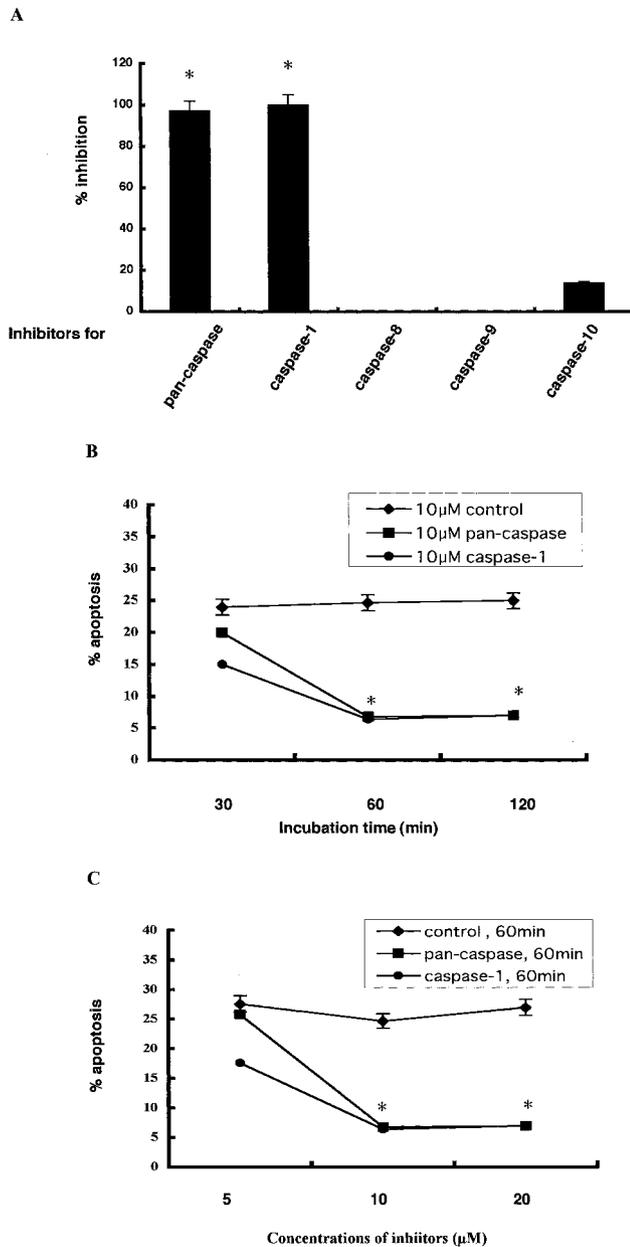


FIGURE 4. Suppression of Gal-9-mediated apoptosis by caspase inhibitors (A) in a time- (B) and dose (C)-dependent manner. Cells were incubated with 10 μ M Z-FA-FMK (control), Z-VAD-FMK (pan-caspase inhibitor), Z-YVAD-FMK (caspase-1 inhibitor), Z-IETD-FMK (caspase-8 inhibitor), Z-LEHD-FMK (caspase-9 inhibitor), or Z-AEVD-FMK (caspase-10 inhibitor) for 1 h, followed by 1 μ M rGal-9. Results were shown as the percent inhibition of Gal-9-induced apoptosis. Data are the mean \pm SEM of three experiments. *, $p < 0.05$.

lactose, but not sucrose, suppressed the Gal-9-induced Ca^{2+} influx. A23187 (final concentration, 5 ng/ml), as a control, induced an evident Ca^{2+} influx in MOLT-4 (Fig. 6). We also confirmed the involvement of calpain and Ca^{2+} influx in the Gal-9-induced apoptosis of other cell lines (data not shown).

Ca^{2+} signaling is originated with extracellular and intracellular Ca^{2+} flux. To examine whether Ca^{2+} flux is actually required for Gal-9-mediated apoptosis, we assessed the apoptosis in MOLT-4 preincubated with either the IP_3 inhibitor, 2-APB, or the intracellular Ca^{2+} chelator, BAPTA-AM. To block extracellular Ca^{2+} influx, apoptosis was induced by Gal-9 in the presence or the absence of the extracellular Ca^{2+} chelator, EGTA. Fig. 7 shows that

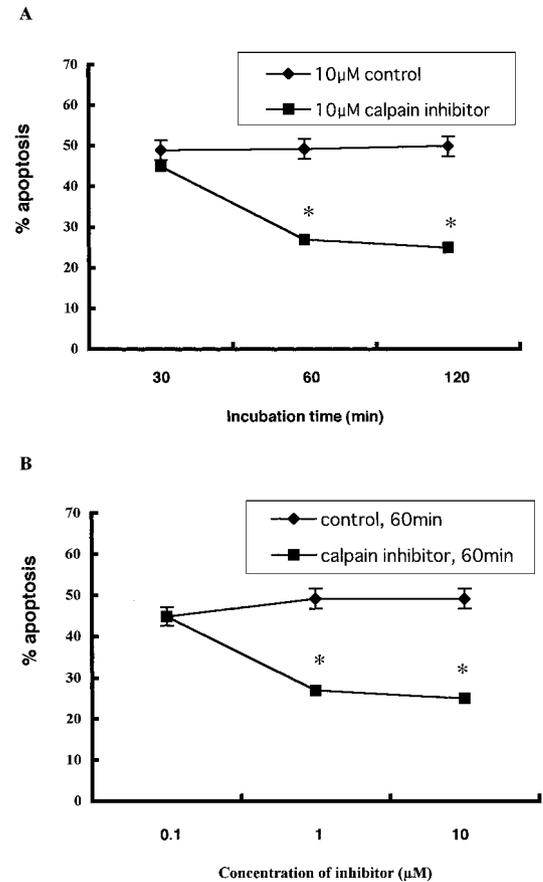


FIGURE 5. Calpain inhibitor inhibits Gal-9 induced apoptosis. Cells were incubated with calpain inhibitor (Z-LLY-FMK) or the control (Z-FA-FMK) at the indicated concentration for 1 h, followed by 1 μ M rGal-9. Results were shown as percent inhibition of Gal-9-induced apoptosis. Data show the mean \pm SEM of three experiments. *, $p < 0.05$.

both BAPTA-AM and 2-APB at least partially suppressed Gal-9-induced apoptosis. In contrast, little suppression was induced by EGTA (Fig. 7). Thus, intracellular, but not extracellular, Ca^{2+} flux may be involved in Gal-9-mediated apoptosis.

Discussion

Numerous reports concerning galectin-induced apoptosis have been published after the description of Gal-1-induced T cell apoptosis (24). To date, other galectins, such as Gal-7 (28–30), Gal-8 (46), and Gal-12 (47), have been shown to be proapoptotic, whereas Gal-3 functions as anti-apoptotic factor (48). Like other galectins, Gal-9 can induce the apoptosis of thymocytes and melanoma cells (12, 15). However, little is known about the pathway involved in Gal-9-induced apoptosis. We first assessed the proapoptotic activity of Gal-9 on various types of cells. The results showed that Gal-9 induced the apoptosis of all immune cells tested, including MOLT-4 and Jurkat cells (Figs. 1 and 3), indicating that Gal-9 functions as a proapoptotic factor for many cell types.

With respect to other stimuli, such as GC, anti-Fas Ab, and oxidative stress, the apoptotic pathways induced by respective stimulus have already been analyzed. For instance, anti-Fas Ab binds to Fas ligand and induces apoptosis through caspase-8 activation (19). Etoposide causes DNA damage and induces mitochondrial cytochrome *c* release, caspase-9 activation, and finally apoptosis (47). GC activates Ca^{2+} -dependent endonuclease and caspase-1 to induce cell death (16–18). Current studies have suggested that GC-induced apoptosis primarily involves caspase-9 initiation (49–51). In the present studies we confirmed that inhibitors

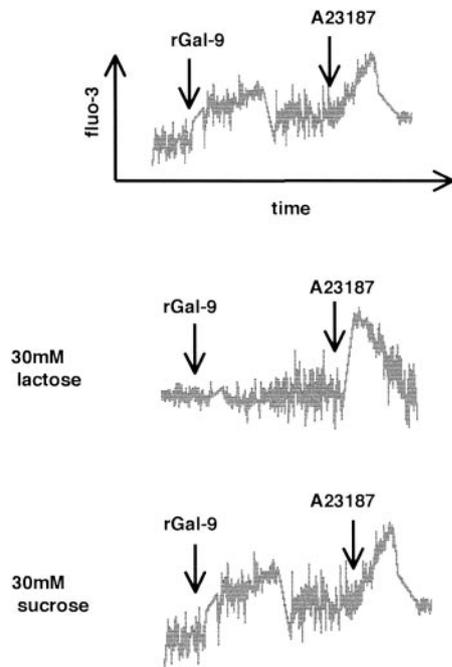


FIGURE 6. Gal-9-induced Ca^{2+} mobilization. Intracellular Ca^{2+} levels were measured in Fluo-3-loaded cells. Arrows indicate the time of stimulation with rGal-9 (6 μM) and A23187 as the positive control. For lactose inhibition assay, cells suspended in 30 mM lactose were stimulated with rGal-9 (6 μM) and A23187. Cells were also suspended in 30 mM sucrose as a control. Representative data from four experiments are presented.

for both caspase-1 and caspase-9 suppress DEX-mediated apoptosis (data not shown).

The present study found that Gal-9 induces apoptosis following Ca^{2+} mobilization (Fig. 6) and calpain (Fig. 5) and caspase-1 activation (Fig. 4), indicating that Gal-9 uses the Ca^{2+} -calpain-caspase-1 pathway to induce apoptosis. Furthermore, Gal-9-induced apoptosis was inhibited by either the intracellular Ca^{2+} chelator, BAPTA-AM, or the IP_3 inhibitor, 2-APB, but not by the extracellular Ca^{2+} chelator, EGTA (Fig. 7). These results suggest that the pathway of Gal-9-mediated apoptosis differs from that induced by other stimuli, such as GC, anti-Fas, and etoposide.

It is important to compare Gal-9-mediated apoptosis with that mediated by other galectins. The Gal-1 gene is overexpressed during GC-induced cell death (52). Gal-1-induced apoptosis does not require an increase in intracellular Ca^{2+} (28), and Gal-1 fails to induce the apoptosis of Jurkat cells (24), although it induces Ca^{2+} mobilization in Jurkat cells (53). The apoptotic pathway induced by Gal-9 may differ from that induced by Gal-1, because Gal-9 induces the apoptosis of many types of cells, including Jurkat cells (Fig. 3A), and Ca^{2+} influx is required for Gal-9-mediated apoptosis (Fig. 7). Gal-1-mediated apoptosis occurs very rapidly; it is detected after 30 min of Gal-1 binding (24, 54), indicating that no de novo protein synthesis may be required, although Rabinovich and co-workers (55) have suggested that transcription is required for Gal-1-induced apoptosis. In contrast, Gal-9 may require a longer binding period and de novo protein synthesis to exhibit proapoptotic activity differing from Gal-1-mediated apoptosis (Fig. 2, A and B). However, the present data may not absolutely support the requirement of protein synthesis for Gal-9-mediated apoptosis, since the complete suppression was not induced at cycloheximide levels that do not increase background death (Fig. 2B). Further studies are therefore required to ascertain the requirement of protein synthesis for Gal-9-mediated cell death, but it is at least clear that death occurs with the machinery present in the cell.

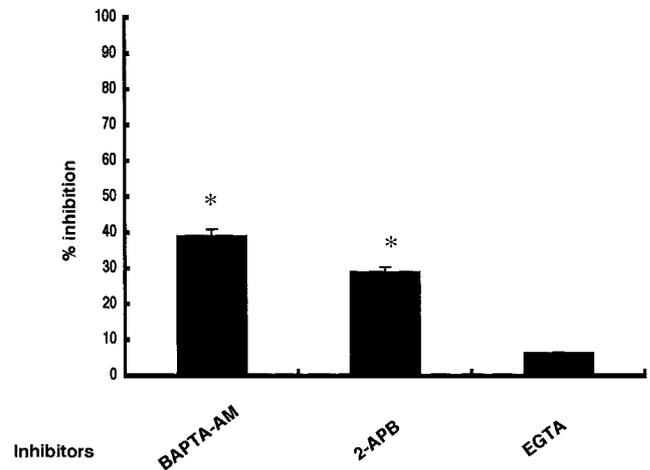


FIGURE 7. Suppression of Gal-9-induced apoptosis by inhibition of Ca^{2+} mobilization. Cells were incubated with or without 30 μM BAPTA-AM or 10 μM 2-APB, then apoptosis was induced with 1 μM rGal-9. For the Ca^{2+} -free medium assay, cells were suspended in 1.8 mM Ca^{2+} -containing medium or in 4 mM EGTA in Ca^{2+} -free medium. Results were shown as the percent inhibition of Gal-9-induced apoptosis. Data represent the mean \pm SEM of three experiments. *, $p < 0.05$.

Gal-7 also appears to be a proapoptotic galectin that functions intracellularly upstream of c-Jun N-terminal kinase activation and cytochrome *c* release (29, 30). Mitochondrial events may not be involved in Gal-9-induced apoptosis, because an inhibitor for caspase-9 essentially required for mitochondria-associated apoptosis (21) did not suppress Gal-9-mediated apoptosis (Fig. 4A). Further signal transduction studies are required to compare precisely Gal-9-mediated cell death and those mediated by other stimuli.

We have found that the release of Gal-9 from Jurkat cells is induced by PMA stimulation (56). Furthermore, Jurkat cells release negligible Gal-9 unless stimulated by PMA, whereas they express Gal-9 on their surface (56). It thus becomes important to clarify the reason why Jurkat cells expressing Gal-9 on the cell surface can survive. Two possibilities are that exogenously added Gal-9 or released Gal-9, but not surface-bound Gal-9, is involved in the apoptosis, or that exogenously added Gal-9 accesses different cell surface receptors than endogenous Gal-9.

It is well known that activated T cells undergo apoptosis more easily than resting T cells (57). Indeed, we have found that Gal-9 induces apoptosis in activated CD4^+ and CD8^+ T cells in human peripheral blood cells, whereas it does not induce apoptosis of resting T cells (Fig. 3B). These results suggest that cell surface Gal-9 binding molecules responsible for apoptosis are expressed during stimulation with anti-CD3. Tuchiya et al. (58) have shown that Gal-9 induces the selective apoptosis of activated CD8^+ , but not CD4^+ , splenic T cells in nephritic rats. However, Gal-9 induces much more apoptosis in activated CD4^+ T cells than in CD8^+ T cells in human peripheral blood cells (Fig. 3B). This discrepancy may be ascribed to the differences in tissue or animal, although further studies are required to ascertain the reason for this.

From the results of the present experiments, human Gal-9 induces the apoptosis of various immune cells, including activated CD4^+ and CD8^+ T cells, through the Ca^{2+} -calpain-caspase-1 pathway, suggesting that Gal-9 plays a role not only in thymocyte maturation, but also in immunomodulation, by inducing the apoptosis of those cells.

References

- Matsumoto, R., H. Matsumoto, M. Seki, M. Hata, Y. Asano, S., Kanegasaki, R. L. Stevens, and M. Hirashima. 1998. Human ecallectin, a variant of human

- galectin-9, is a novel eosinophil chemoattractant produced by T lymphocytes. *J. Biol. Chem.* 273:16976.
2. Wada, J., and Y. S. Kanwar. 1997. Identification and characterization of galectin-9, a novel β -galactoside-binding mammalian lectin. *J. Biol. Chem.* 272:6078.
 3. Hirashima, M. 1999. Ecalectin as a T cell-derived eosinophil chemoattractant. *Int. Arch. Allergy. Immunol.* 120(Suppl. 1):7.
 4. Barondes, S. H., V. Castronovo, D. N. Cooper, R. D. Cummings, K. Drickame, T. Feizi, M. A. Gitt, J. Hirabayashi, C. Hughes, K. Kasai, et al. 1994. Galectins: a family of animal β -galactoside-binding lectins. *Cell* 76:597.
 5. Barondes, S. H., D. N. Cooper, M. A. Gitt, and H. Leffler. 1994. Galectins: structure and function of a large family of animal lectins. *J. Biol. Chem.* 269:20807.
 6. Robertson, M. W., K. Albrandt, D. Keller, and F. T. Liu. 1990. Human IgE-binding protein: a soluble lectin exhibiting a highly conserved interspecies sequence and differential recognition of IgE glycoforms. *Biochemistry* 29:8093.
 7. Oda, Y., J. Herrmann, M. A. Gitt, C. W. Turck, A. L. Burlingame, S. H. Barondes, and H. Leffler. 1993. Soluble lactose-binding lectin from rat intestine with two different carbohydrate-binding domains in the same peptide chain. *J. Biol. Chem.* 268:5929.
 8. Hadari, Y. R., K. Paz, R. Dekel, T. Mestrovic, D. Accili, and Y. Zick. 1995. Galectin-8: a new rat lectin, related to galectin-4. *J. Biol. Chem.* 270:3447.
 9. Rabinovich, G. A. 1999. Galectins: an evolutionarily conserved family of animal lectins with multifunctional properties; a trip from the gene to clinical therapy. *Cell Death Differ.* 6:711.
 10. Perillo, N. L., M. E. Marcus, and L. G. Baum. 1998. Galectins: versatile modulators of cell adhesion, cell proliferation, and cell death. *J. Mol. Med.* 76:402.
 11. Liu, F. T. 2000. Galectins: a new family of regulators of inflammation. *Clin. Immunol.* 97:79.
 12. Wada, J., K. Ota, A. Kumar, E. I. Wallner, and Y. S. Kanwar. 1997. Developmental regulation, expression, and apoptotic potential of galectin-9, a β -galactoside binding lectin. *J. Clin. Invest.* 99:2452.
 13. Hirashima, M. 2000. Ecalectin/galectin-9, a novel eosinophil chemoattractant: its function and production. *Int. Arch. Allergy Immunol.* 122:6.
 14. Blaheta, R. A., M. Franz, M. K. Auth, H. J. Wenisch, and B. H. Markus. 1991. A rapid non-radioactive fluorescence assay for the measurement of both cell number and proliferation. *J. Immunol. Methods* 142:199.
 15. Kageshita, T., Y. Kashio, A. Yamauchi, M. Seki, J. A. Mohammad, N. Nishi, H. Shoji, T. Nakamura, T. Ono, and M. Hirashima. 2002. Possible role of galectin-9 in cell aggregation and apoptosis of human melanoma cell lines and its clinical significance. *Int. J. Cancer* 99:809.
 16. Cheneval, D., P. Ramage, T. Kastelic, T. Szelestenyi, H. Niggli, R. Hemmig, M. Bachmann, and A. MacKenzie. 1998. Increased mature interleukin-1 β (IL-1 β) secretion from THP-1 cells induced by nigericin is a result of activation of p45 IL-1 β -converting enzyme processing. *J. Biol. Chem.* 273:17846.
 17. McConkey, D. J. 1996. Calcium-dependent, interleukin 1-converting enzyme inhibitor-insensitive degradation of lamin B1 and DNA fragmentation in isolated thymocyte nuclei. *J. Biol. Chem.* 271:22398.
 18. Cohen, J. J., and R. C. Duke. 1984. Glucocorticoid activation of a calcium-dependent endonuclease in thymocyte nuclei leads to cell death. *J. Immunol.* 132:38.
 19. Sun, X. M., M. MacFarlane, J. Zhuang, B. B. Wolf, D. R. Green, and G. M. Cohen. 1999. Distinct caspase cascades are initiated in receptor-mediated and chemical-induced apoptosis. *J. Biol. Chem.* 274:5053.
 20. Wen, J., N. Ramadevi, D. Nguyen, C. Perkins, E. Worthington, and K. Bhalla. 2000. Antileukemic drugs increase death receptor 5 levels and enhance Apo-2L-induced apoptosis of human acute leukemia cells. *Blood* 96:3900.
 21. Li, M., T. Kondo, Q. L. Zhao, F. J. Li, K. Tanabe, Y. Arai, Z. C. Zhou, and M. Kasuya. 2000. Apoptosis induced by cadmium in human lymphoma U937 cells through Ca²⁺-calpain and caspase-mitochondria-dependent pathways. *J. Biol. Chem.* 275:39702.
 22. Fernandes-Alnemri, T., R. C. Armstrong, J. Krebs, S. M. Srinivasula, L. Wang, F. Bullrich, L. C. Fritz, J. A. Trapani, K. J. Tomaselli, G. Litwack, et al. 1996. In vitro activation of CPP32 and Mch3 by Mch4, a novel human apoptotic cysteine protease containing two FADD-like domains. *Proc. Natl. Acad. Sci. USA* 93:7464.
 23. Froelich, C. J., V. M. Dixit, and X. Yang. 1998. Lymphocyte granule-mediated apoptosis: matters of viral mimicry and deadly proteases. *Immunol. Today* 19:30.
 24. Perillo, N. L., K. E. Pace, J. J. Seilhamer, and L. G. Baum. 1995. Apoptosis of T cells mediated by galectin-1. *Nature* 378:736.
 25. Perillo, N. L., C. H. Uittenbogaart, J. T. Nguyen, and L. G. Baum. 1997. Galectin-1, an endogenous lectin produced by thymic epithelial cells, induces apoptosis of human thymocytes. *J. Exp. Med.* 185:1851.
 26. Ellerhorst, J., T. Nguyen, D. N. Cooper, Y. Estrov, D. Lotan, and R. Lotan. 1999. Induction of differentiation and apoptosis in the prostate cancer cell line LNCaP by sodium butyrate and galectin-1. *Int. J. Oncol.* 14:225.
 27. Rabinovich, G. A., C. R. Alonso, C. E. Sotomayor, S. Durand, J. L. Bocco, and C. M. Riera. 2000. Molecular mechanisms implicated in galectin-1-induced apoptosis: activation of the AP-1 transcription factor and downregulation of Bcl-2. *Cell Death Differ.* 7:747.
 28. Pace, K. E., H. P. Hahn, M. Pang, J. T. Nguyen, and L. G. Baum. 2000. CD7 delivers a pro-apoptotic signal during galectin-1-induced T cell death. *J. Immunol.* 165:2331.
 29. Kuwabara, I., Y. Kuwabara, R. Y. Yang, M. Schuler, D. R. Green, B. L. Zuraw, D. K. Hsu, and F. T. Liu. 2002. Galectin-7 (PIG1) exhibits pro-apoptotic function through JNK activation and mitochondrial cytochrome c release. *J. Biol. Chem.* 277:3487.
 30. Bernerd, F., A. Sarasin, and T. Magnaldo. 1999. Galectin-7 overexpression is associated with the apoptotic process in UVB-induced sunburn keratinocytes. *Proc. Natl. Acad. Sci. USA* 96:11329.
 31. Matsushita, N., N. Nishi, M. Seki, R. Matsumoto, I. Kuwabara, F. T. Liu, Y. Hata, T. Nakamura, and M. Hirashima. 2000. Requirement of divalent galactoside-binding activity of ecalectin/galectin-9 for eosinophil chemoattraction. *J. Biol. Chem.* 275:8355.
 32. Nishi, N., H. Shoji, H. Miyanaka, and T. Nakamura. 2000. Androgen-regulated expression of a novel member of the Aldo-keto reductase superfamily in regrowing rat prostate. *Endocrinology* 141:3194.
 33. Sandstrom, K., L. Hakansson, A. Lukinius, and P. Venge. 2000. A method to study apoptosis in eosinophils by flow cytometry. *J. Immunol. Methods* 240:55.
 34. Zhang, L., K. Mizumoto, N. Sato, T. Ogawa, M. Kusumoto, H. Niiyama, and M. Tanaka. 1999. Quantitative determination of apoptotic death in cultured human pancreatic cancer cells by propidium iodide and digitonin. *Cancer Lett.* 142:129.
 35. Ramdas, J., and J. M. Hamron. 1998. Glucocorticoid-induced apoptosis and regulation of NF- κ B activity in human leukemic T cells. *Endocrinology* 139:3813.
 36. Vu, C. C., C. D. Bortner, and J. A. Cidlowski. 2001. Differential involvement of initiator caspases in apoptotic volume decrease and potassium efflux during Fas- and UV-induced cell death. *J. Biol. Chem.* 276:37602.
 37. Sweeney, E. A., J. Inokuchi, and Y. Igarashi. 1998. Inhibition of sphingolipid induced apoptosis by caspase inhibitors indicates that sphingosine acts in an earlier part of the apoptotic pathway than ceramide. *FEBS Lett.* 425:61.
 38. Abbey, S. E., and L. R. Potter. 2002. Vasopressin-dependent inhibition of the C-type natriuretic peptide receptor, NPR-B/GC-B, requires elevated intracellular calcium concentrations. *J. Biol. Chem.* 277:42423.
 39. Qu, X., Y. Qi, P. Lan, and Q. Li. 2002. The novel endoplasmic reticulum (ER)-targeted protein HAP induces cell apoptosis by the depletion of the ER Ca²⁺ stores. *FEBS Lett.* 529:325.
 40. Maruyama, T., T. Kanaji, S. Nakade, T. Kanno, and K. Mikoshiba. 1997. 2APB, 2-aminoethoxydiphenyl borate, a membrane-penetrable modulator of Ins(1,4,5)P₃-induced Ca²⁺ release. *J. Biochem.* 122:498.
 41. Wang, Y., M. Deshpande, and R. Payne. 2002. 2-Aminoethoxydiphenyl borate inhibits phototransduction and blocks voltage-gated potassium channels in Limulus ventral photoreceptors. *Cell Calcium* 32:209.
 42. Sharp, B. M., N. A. Shahabi, W. Heagy, K. McAllen, M. Bell, C. Huntoon, and D. J. McKean. 1996. Dual signal transduction through delta opioid receptors in a transfected human T-cell line. *Proc. Natl. Acad. Sci. USA* 93:8294.
 43. Sano, H., D. K. Hsu, L. Yu, J. R. Appar, I. Kuwabara, T. Yamanaka, M. Hirashima, and F. T. Liu. 2000. Human galectin-3 is a novel chemoattractant for monocytes and macrophages. *J. Immunol.* 165:2156.
 44. Vancompernelle, K., F. Van Herreweghe, G. Vanaert, M. Van de Craen, K. De Vos, N. Totty, A. Sterling, W. Fiers, P. Pandoabele, and J. Grooten. 1998. Attractylolide-induced release of cathepsin B, a protease with caspase-processing activity. *FEBS Lett.* 438:150.
 45. Wang, K. K., R. Posmantur, R. Nadimpalli, R. Nath, P. Mohan, R. A. Nixon, R. V. Talanian, M. Keegan, L. Herzog, and H. Allen. 1998. Caspase-mediated fragmentation of calpain inhibitor protein calpastatin during apoptosis. *Arch. Biochem. Biophys.* 356:187.
 46. Hadari, Y. R., R. Arbel-Goren, Y. Levy, A. Amsterdam, R. Alon, R. Zakut, and Y. Zick. 2000. Galectin-8 binding to integrins inhibits cell adhesion and induces apoptosis. *J. Cell Sci.* 113:2385.
 47. Hotta, K., T. Funahashi, Y. Matsukawa, M. Takahashi, H. Nishizawa, K. Kishida, M. Matsuda, H. Kuriyama, S. Kihara, T. Nakamura, et al. 2001. Galectin-12, an adipose-expressed galectin-like molecule possessing apoptosis-inducing activity. *J. Biol. Chem.* 276:34089.
 48. Yang, R. Y., D. K. Hsu, and F. T. Liu. 1996. Expression of galectin-3 modulates T-cell growth and apoptosis. *Proc. Natl. Acad. Sci. USA* 93:6737.
 49. Hakem, R., A. Hakem, G. S. Duncan, J. T. Henderson, M. Woo, M. S. Soengas, A. Elia, J. L. de la Pompa, D. Kagi, W. Khoo, et al. 1998. Differential requirement for caspase 9 in apoptotic pathways in vivo. *Cell* 94:339.
 50. Kuida, K., T. F. Haydar, C. Y. Kuan, Y. Gu, C. Taya, H. Karasuyama, M. S. Su, P. Rakic, and R. A. Flavell. 1998. Reduced apoptosis and cytochrome c-mediated caspase activation in mice lacking caspase 9. *Cell* 94:325.
 51. Distelhorst, C. W. 2002. Recent insights into the mechanism of glucocorticosteroid-induced apoptosis. *Cell Death Differ.* 9:6.
 52. Goldstone, S. D., and M. F. Lavin. 1991. Isolation of a cDNA clone, encoding a human β -galactoside binding protein, overexpressed during glucocorticoid-induced cell death. *Biochem. Biophys. Res. Commun.* 178:746.
 53. Walzel, H., M. Blach, J. Hirabayashi, K. I. Kasai, and J. Brock. 2000. Involvement of CD2 and CD3 in galectin-1 induced signaling in human Jurkat T-cells. *Glycobiology* 10:131.
 54. Pace, K. E., C. Lee, P. L. Stewart, and L. G. Baum. 1999. Restricted receptor segregation into membrane microdomains occurs on human T cells during apoptosis induced by galectin-1. *J. Immunol.* 163:3801.
 55. Rabinovich, G. A., C. R. Alonso, C. E. Sotomayor, S. Durand, J. L. Bocco, and C. M. Riera. 2000. Molecular mechanisms implicated in galectin-1-induced apoptosis: activation of the AP-1 transcription factor and downregulation of Bcl-2. *Cell Death Differ.* 7:747.
 56. Chabot, S., Y. Kashio, M. Seki, Y. Shirato, K. Nakamura, N. Nishi, T. Nakamura, R. Matsumoto, and M. Hirashima. 2002. Regulation of galectin-9 expression and release in Jurkat T cell line cells. *Glycobiology* 12:111.
 57. Janssen, O., S. Wesselborg, B. Heckl-Ostreicher, K. Pechhold, A. Bender, S. Schöndelmaier, G. Moldenhauer, and D. Kabelitz. 1991. T cell receptor/CD3-signaling induces death by apoptosis in human T cell receptor $\gamma\delta^+$ T cells. *J. Immunol.* 146:35.
 58. Tsuchiyama, Y., J. Wada, H. Zhang, Y. Morita, K. Hiragushi, K. Hida, K. Shikata, M. Yamamura, Y. S. Kanwar, and H. Makino. 2000. Efficacy of galectins in the amelioration of nephrotoxic serum nephritis in Wistar Kyoto rats. *Kidney Int.* 58:1941.