Sphingosine Contributes to Glucocorticoid-Induced Apoptosis of Thymocytes Independently of the Mitochondrial Pathway

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Sphingosine Contributes to Glucocorticoid-Induced Apoptosis of Thymocytes Independently of the Mitochondrial Pathway

Sandrine Lépine,* Boris Lakatos,³ Marie-Pierre Courageot,* Hervé Le Stunff,† Jean-Claude Sulpice,* and Françoise Giraud**

During the selection process in the thymus, most thymocytes are eliminated by apoptosis through signaling via TCR or glucocorticoids. The involvement of ceramide (Cer) and sphingosine (SP), important apoptotic mediators, remains poorly defined in glucocorticoid-induced apoptosis. We report that, in mouse thymocytes, apoptosis triggered by 10⁻⁶ M dexamethasone (DX) was preceded by a caspase-dependent Cer and SP generation, together with activation of acidic and neutral ceramidases. Apoptosis was drastically reduced by blocking either sphingolipid production (by acid sphingomyelinase inhibitor) or SP production (by ceramidase inhibitors), but not by inhibition of de novo Cer synthesis. Thus, SP generated through acid sphingomyelinase and ceramidase activity would contribute to the apoptotic effect of DX. Consistent with this hypothesis, SP addition or inhibition of SP ceramidase inhibitors, but not by inhibition of de novo Cer synthesis. DX induced a proteasome-dependent loss of mitochondrial membrane potential (Δψₘ) and caspase-8, -3, and -9 processing. Apoptosis was abolished by inhibition of Δψₘ loss or caspase-8 or -3, but not caspase-9. Δψₘ loss was independent of SP production and caspase-8, -3, and -9 activation. However, inhibition of SP production reduced caspase-8 and -3, but not caspase-9 processing. Proteasome inhibition impaired activation of the three caspases, whereas inhibition of Δψₘ loss solely blocked caspase-9 activation. These data indicate that DX-induced apoptosis is mediated in part by SP, which contributes, together with proteasome activity, to caspase-8-3 processing independently of mitochondria, and in part by the proteasome/mitochondria pathway, although independently of caspase-9 activation. The Journal of Immunology, 2004, 173: 3783–3790.

In the thymus, positive and negative selection steps prevent nonfunctional or harmful T cells from reaching the periphery. Glucocorticoid-induced apoptosis contributes to the elimination of thymocytes during clonal selection and to the creation of a fully functional immune system (1). The glucocorticoid receptor, an essential and widely expressed transcriptional regulator, is triggered by hormone binding to translocate to the nucleus, activating or repressing transcription depending on the cell and gene context (2).

Sphingolipid metabolites, ceramide (Cer) and sphingosine (SP), are now recognized as key regulators of apoptosis, cell prolifera
upon DX stimulation was proposed to mediate caspase-8 activation upstream of mitochondrial resulting, on one hand, in cytochrome c release and caspase-9-3 activation and, in contrast, in direct activation of caspase-3 (16). Furthermore, mitochondria and proteasomes are involved in thymocyte cell death in response to DX. Indeed, apoptosis is blocked by Bcl-2 and Bcl-x<sub>1</sub>, overexpression and by inhibition of the mitochondrial inner membrane potential (ΔΨ<sub>m</sub>) loss and of cytochrome c release (20–24). Inhibition of protease activity abolishes ΔΨ<sub>m</sub> loss, cytochrome c release, and caspase-3 activity, and protects thymocytes against a number of apoptosis inducers including DX, suggesting that proteasomes exert their regulatory role at a premitochondrial step during thymocyte apoptosis (22, 25, 26).

In the present study, we investigated the relationships between sphingolipid metabolism, proteasome-mitochondria pathway, and caspase-processing in DX-induced apoptosis of murine thymocytes. We show that both Cer and SP are apoptotic mediators in these cells. In response to DX, SP was produced through the sequential activation of aSMase and Cerases in a caspase-dependent manner and mediated cell death by contributing to caspase-8-3 processing through a mitochondria-independent pathway.

Materials and Methods

Reagents

Adenosine, aprotinin, bongkrekic acid (BA), β-chloroalanine (β-CL), t-cyclosine (CS), DX, 4-deoxyripiroxidinio, dioleyl phosphatidylethanolglycerol, fumonisin B1 (FB1), leupeptin, N-acetyl ethanolamine (NOE), PMA, αSMase from Staphylococcus aureus, aSMase from human placenta, and peroxidase-conjugated goat anti-rabbit IgG were obtained from Sigma-Aldrich (St. Louis, MO). Diacylglycerol (DAG) kinase and (1S,2R)-o-erythro-2-(N-myristyloxy)-1-phenyl-1-propanol (N-MAPP) were from Calbiochem (San Diego, CA). o-Erythro-sphingosine (SP), N,N-dimethyl sphingosine (DMS), and MG132 were from Alexis (Lausen, Switzerland). C12-NBD-Cer (NBD-C12:0, d18:1) (NBD-Cer) was obtained from Avanti (Alabaster, AL). The protein assay kit was from Bio-Rad (Hercules, CA), and [<sup>32</sup>P]ATP was purchased from PerkinElmer Life Sciences (Wellesley, MA). 3,3′-Diethoxyacyclobacine iodeide (ΔO<sub>C</sub>(5)) was obtained from Fluka (Buchs, Switzerland), and caspase inhibitors N-benzoyloxy-carbonyl-Val-Ala-Asp-, Ile-Glu-Thr-Asp-, Leu-Glu-His-Asp-, and Asp-Glu-Val-Asp-fluoromethylketone (Z-VAD; Z-IEETD; Z-LEHD; Z-DEVDD) were from R&D Systems (Minneapolis, MN). Rabbit anti-caspase-3, -8, and -9 were provided by Santa Cruz Biotechnology (Santa Cruz, CA). (2-Iso-isopropyl-1-(4-[3-caspase-3, -8, and -9 were provided by Santa Cruz Biotechnology (Santa Cruz, CA). (2-Iso-isopropyl-1-[3-(N-methyl-N-(3,4-dimethoxy-β-

Animals and cell culture

Thymocytes from male 3- to 6-wk-old BALB/c mice (2.5 or 5 × 10<sup>6</sup> cells) were cultured at 37°C in 5% CO<sub>2</sub> in HEPES-RPMI 1640 medium containing 15% heat-inactivated FCS. When required, cells were incubated with 10 ng/ml leupeptin and 100 μg/ml leupeptin and 10 μg/ml BAPN, 0.5 mM PMSF, 2 mM DTT, and 0.5 mM 4-deoxyripiroxidinio and centrifuged at 4°C (10 min; 100,000 × g). The supernatant (cytosol) was collected and kept frozen at −80°C. After incubation, thymocytes (10<sup>7</sup> cells) were washed in ice-cold buffer A and centrifuged at 4°C (5 min; 200 × g). The pellet was lyzed as described above and extracted with 2 ml of chloroform/methanol (2:1). The aqueous phase was extracted once more, and the organic phases were pooled, dried, and used for SP and phosphatase measurements. SP levels were determined essentially as described previously (29). Sphingosine-1-<sup>32</sup>P was detected and quantified by a phosphor imager. SP levels were normalized to total lipid phosphate. SP kinase activity was determined as described previously (30), on thymocyte cytosol (50 μg of protein) from the phosphorylation of added SP (50 μM).

Cerase assay

After incubation, thymocytes (2.5 × 10<sup>7</sup> cells) were washed in ice-cold buffer A and centrifuged at 4°C (5 min; 200 × g). Cell pellets were lyzed for 10 min on ice in 0.2% Triton X-100 and 10 mM Tris-HCl (pH 7.4), and centrifuged at 4°C (5 min; 14,000 × g). Supernatants (cytosol) were homogenized with three passes through a 25-gauge needle. Cerase activity was determined using NBD-Cer, added from a 300 mM ethanolic solution to a final concentration of 1.5 μM, and incubated for 10 min at 4°C. Aliquots (150 μl, containing ~40 μg of protein) were mixed with 150 μl of buffers containing 0.2% Triton X-100 and 0.5 mM Na acetate (pH 4.5) for acidic Cerase, 10 mM Tris-HCl (pH 7.4) for neutral Cerase, or 10 mM NaOH-HEPES (pH 9.5) for alkaline Cerase, and incubated for 1 h at 37°C. After addition of 300 μl of 0.2 N HCl, followed by 2.4 ml of chloroform/methanol (1:1) and 1.2 ml of H<sub>2</sub>O, the organic phase was dried and solubilized in chloroform/methanol (2:1) for lipid analysis by TLC in chloroform/methanol/ammonia (20%) (90:20:8). The fluorescence of NBD-dodecanoic acid was detected at 450/530-nm excitation/emission wavelengths, quantified by a phosphor imager, and used to estimate the enzymatic activity.

Assay for mitochondrial transmembrane potential

ΔΨ<sub>m</sub> was measured by accumulation of ΔO<sub>C</sub>(3) to the mitochondria matrix space by flow cytometry (21). After incubation, thymocytes (10<sup>7</sup> cells) were loaded with 40 nM ΔO<sub>C</sub>(3) and incubated for 20 min at 37°C. The stained cells were analyzed by FACS (BD Biosciences, Mountain View, CA).

Western blot analysis

After incubation, thymocytes (4 × 10<sup>6</sup> cells) were washed three times in ice-cold buffer A, lysed for 30 min on ice in 250 mM sucrose, 1 mM EDTA, 1 mM PMSF, 10 μg/ml leupeptin and apropin, 0.05% Triton X-100, 1 mM DTT, and 20 mM Tris-HCl (pH 7.4), and centrifuged at 4°C (15 min; 14,000 × g). The proteins of the supernatant were separated by SDS-PAGE on 15% gels and transferred onto polyvinylidene difluoride membranes. After incubation of the membranes with primary and secondary Abs, proteins were visualized by ECL.
Student's t of thymocytes with 10^{-8} M DX at 2.5 h treatment (data not shown). Incubation of thymocytes for 5 h with 10^{-6} M DX or 100 nM PMA, without (control) or with 50 μM FB1, 300 μM CS, 5 nM β-Cl, or 20 μM SR33557 (SR); apoptosis was evaluated from the percentage of cells with apoptotic nuclei (means ± SE of three to five experiments). * , Significantly different from DX- or PMA-treated cells. E and F, Thymocytes were incubated for the indicated times with either 10^{-8} (E) or 10^{-6} M DX (F); SP levels were measured by the SP kinase assay and expressed as percentage of the basal level (time 0) (means ± SE of four to six experiments). Basal levels of Cer and SP in thymocytes were ~1.5 and 0.2 pmol/nmol of phospholipid, respectively.

Statistical analysis
Data are expressed as means ± SEM. Significance was assessed by the Student’s t test for paired samples. Values of p < 0.05 were considered significant.

Results
DX-induced apoptosis is preceded by Cer and SP generation and does not involve de novo Cer synthesis. A, Thymocytes were incubated for 5 h with different concentrations of DX; apoptosis was evaluated from the percentage of cells with apoptotic nuclei (means ± SE of three to five experiments). B and C, Thymocytes were incubated for the indicated times with either 10^{-8} (B) or 10^{-6} M DX (C); Cer levels were measured by the DAG kinase assay and expressed as percentage of the basal level (time 0) (means ± SE of four to six experiments). D, Thymocytes were incubated for 5 h with 10^{-6} M DX or 100 nM PMA, without (control) or with 50 μM FB1, 300 μM CS, 5 nM β-Cl, or 20 μM SR33557 (SR); apoptosis was evaluated from the percentage of cells with apoptotic nuclei (means ± SE of three to five experiments). * , Significantly different from DX- or PMA-treated cells. E and F, Thymocytes were incubated for the indicated times with either 10^{-8} (E) or 10^{-6} M DX (F); SP levels were measured by the SP kinase assay and expressed as percentage of the basal level (time 0) (means ± SE of four to six experiments). Basal levels of Cer and SP in thymocytes were ~1.5 and 0.2 pmol/nmol of phospholipid, respectively.

### Table I. Effects of Z-VAD, MG132, or SR33557 on DX-induced sphingolipid production

<table>
<thead>
<tr>
<th></th>
<th>Cer</th>
<th>SP</th>
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<tbody>
<tr>
<td>None</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Z-VAD</td>
<td>99 ± 12</td>
<td>112 ± 8</td>
</tr>
<tr>
<td>DX</td>
<td>196 ± 12</td>
<td>153 ± 10</td>
</tr>
<tr>
<td>+Z-VAD</td>
<td>111 ± 16*</td>
<td>107 ± 7*</td>
</tr>
<tr>
<td>None</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>MG132</td>
<td>108 ± 9</td>
<td></td>
</tr>
<tr>
<td>SR33557</td>
<td>134 ± 14**</td>
<td></td>
</tr>
<tr>
<td>DX</td>
<td>128 ± 8</td>
<td></td>
</tr>
<tr>
<td>+MG132</td>
<td>129 ± 8</td>
<td></td>
</tr>
<tr>
<td>+SR33557</td>
<td>128 ± 5</td>
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</table>

* For Cer determination, thymocytes were incubated for 5 min with 10^{-6} M DX, without or with 10 μM Z-VAD, 30 μM MG132, or 20 μM SR33557. For SP determination, thymocytes were incubated for 15 min with 10^{-6} M DX, without or with 10 μM Z-VAD. Cer and SP levels were measured by DAG kinase and SP kinase assays, respectively, and expressed as percentages of basal levels (time 0) (means ± SE of three to four experiments).

* , Significantly different from DX-treated cells.

** , Significantly different from untreated cells.
**SP generated through Cerase activation is involved in DX-induced apoptosis**

In contrast to the persistent Cer accumulation observed at $10^{-6}$ M DX, the transient peak of Cer production detected at $10^{-6}$ M DX suggests that this lipid is more efficiently metabolized in the latter case. Indeed, $10^{-6}$ M DX triggered a modest increase in SP (maximum, 1.5-fold) detectable between 5 and 30 min (Fig. 1E), whereas $10^{-6}$ M DX promoted a larger and more sustained elevation in SP (2- to 2.5-fold) between 10 and 60 min (Fig. 1F). Similarly to Cer generation, SP production induced by DX was abolished by Z-VAD (Table I). Furthermore, treatment with $10^{-6}$ M DX induced a transient activation of both acid and neutral Ceras reaching 50 and 25%, respectively, between 5 and 30 min (Fig. 2, A and B), whereas the activity of alkaline Cerase was not significantly modified (data not shown). In contrast, stimulation with $10^{-6}$ M DX induced a weaker activation of acid Cerase than $10^{-6}$ M (Fig. 2C), without affecting the neutral or alkaline enzymes (data not shown). These data indicate that the accumulation of Cer induced by DX was prevented by its rapid conversion into SP by Ceras, especially when the concentration of DX was $>10^{-6}$ M. To determine whether SP was involved in DX-induced apoptosis, we have used d-MAPP and NOE, two reported Cerase inhibitors (36, 37). Activation of acid and neutral Ceras, induced by $10^{-6}$ M DX in thymocytes, was totally prevented by either d-MAPP or NOE ($10 \mu M$) (Fig. 3A). d-MAPP and NOE potentiated Cer accumulation induced by $10^{-6}$ M DX for 5 min and completely suppressed SP production induced by $10^{-6}$ M DX for 15 min (Fig. 3B). Interestingly, after 5-h incubation, d-MAPP or NOE had no effect on thymocyte cell death, but reduced apoptosis triggered by $10^{-8}$ or $10^{-6}$ M DX (Fig. 3C). The fact that d-MAPP or NOE prevented SP generation and reduced apoptosis in response to DX suggests that SP mediated in part the apoptotic effect of DX in thymocytes.

**Increasing cellular levels of SP or Cer induces apoptosis in the absence of DX**

Exposure of thymocytes to exogenous SP for 3 h induced apoptosis in a dose-dependent manner (Fig. 4A). FB1 did not suppress SP-induced apoptosis (Fig. 4B), indicating that the effect of SP on apoptosis seems to be caused by itself rather than by its acylation into Cer. Similarly, DMS (5 μM), a competitive inhibitor of SP kinase (38), which was able to inhibit thymocyte SP kinase activity after 30-min treatment (data not shown), induced apoptosis after 3-h incubation (Fig. 4A). Treatment of thymocytes with exogenous aSMase promoted a significant increase in both Cer and SP levels, whereas exogenous nSMase triggered a strong increase in Cer without affecting SP level (Fig. 4C). Interestingly, both SMases induced apoptosis of ~30% of cells after 4-h incubation (Fig. 4D). DNA ladder analysis revealed that SP, DMS, and both SMases induced thymocyte apoptosis after 5-h treatment (Fig. 4, E and F). However, only apoptosis induced by aSMase was significantly inhibited by d-MAPP or NOE (Fig. 4D), suggesting that aSMase promoted apoptosis, at least in part, through SP generation, whereas nSMase mediated its effect through Cer production. Together, these data show that the increase in SP level, induced either by exogenous addition or indirectly by SP kinase inhibition or exogenous aSMase, resulted in thymocyte apoptosis.

**The proteasome/mitochondrial pathway is not involved in sphingolipid-mediated apoptosis in response to DX**

In DX-stimulated thymocytes, apoptosis is mediated, at least in part, by proteasome activity required for mitochondrial alterations...
and involves caspase activation (22, 24, 26). In agreement with previous reports (21, 22), we found that MG132 (30 μM), a proteasome inhibitor, and BA (50 μM), an inhibitor of the permeability transition pore (PTP), which stabilizes the Δψm, and prevents the postmitochondrial manifestations of apoptosis, reduced DX-induced apoptosis by ~70% (data not shown). In contrast, Z-VAD (10 μM) totally abolished DX-induced apoptosis (see Fig. 6A). MG132 by itself had no effect on Cer level and did not block Cer production induced by DX (Table I), indicating that proteasome activity was not required for Cer generation. As already reported (22, 23), DX stimulation of thymocytes led to a gradual disruption of Δψm, affecting 65% of cells after 5 h (Fig. 5A) and was abrogated by BA (Fig. 5B). Δψm dissipation was also reduced by MG132, as expected for a role of proteasome activity upstream from mitochondrial changes (21, 22). In contrast, neither Z-VAD nor any of the specific caspase inhibitors tested (Z-IETD, Z-DEVD, Z-LEHD) were able to affect Δψm loss induced by DX, indicating that the processing of caspases, and especially of caspase-8, -3, and -9, occurred downstream and/or independently of mitochondrial damage. SR33557 alone induced a loss of Δψm in ~60% of cells, an extent similar to that triggered by DX, which prevented us from determining whether it could inhibit the effect of DX on Δψm loss. Nevertheless, D-MAPP or NOE were unable to affect DX-induced Δψm loss (Fig. 5B). Together, these data show that the production of sphingolipids did not depend on the proteasome-mitochondrial pathway, and that SP up-regulated apoptosis independently of this pathway.

Caspase activation involved in DX-mediated apoptosis is dependent on SP generation, proteasome activity, and mitochondrial alterations

In agreement with a previous study using 10−7 M DX for 18 h (16), we found that apoptosis induced by 10−6 M DX for 5 h was inhibited dose dependently by Z-IETD and Z-DEVD, whereas Z-LEHD had almost no effect, indicating that caspase-9 activation is dispensable for apoptosis (Fig. 6A). Processing of caspase-8, -3, and -9, analyzed by immunoblotting, became detectable after 2- to 3-h stimulation with 10−6 M DX, without any striking difference in the activation kinetic of each caspase (data not shown). SR33557, as well as D-MAPP or NOE, decreased DX-mediated processing of caspase-8 (Fig. 6B), indicating that SP mediates, at least in part, caspase-8 activation. SR33557, D-MAPP, or NOE also reduced caspase-3 processing, consistent with direct activation of caspase-3 by caspase-8 (39). Activation of caspase-8 and -3 was attenuated by MG132 (Fig. 6B), indicating that, in addition to SP, the proteasome activity also contributes to the activation of the caspase-8-3 cascade. However, the processing of caspase-8-3 was independent of mitochondrial alterations, because it was unaffected by BA. Furthermore, MG132 and BA abolished caspase-9 processing, supporting a role of the proteasome/mitochondria pathway in the activation of caspase-9. In contrast, SR33557, D-MAPP, or NOE did not alter caspase-9 processing, showing that SP is not
involved in the proteasome/mitochondria/caspase-9 pathway. Our data suggest that DX-induced apoptosis depends on caspase-8-3 activation mediated by both SP and proteasome activity, but independently of mitochondria. In addition, the proteasome/mitochondria contributes to DX-mediated apoptosis independently of caspase-9 processing.

**Discussion**

A role for Cer in apoptosis has been proposed in several apoptotic models, including DX-mediated thymocyte death (6). In contrast, our data strongly suggest that SP, a Cer metabolite, is involved in signaling apoptosis in response to DX. Indeed, 10^{-8} M DX induced a weak and transient production of Cer, whereas the generation of SP was robust and sustained, concomitant to the activation of acid and neutral Cerases, and preceded the appearance of nuclear condensation. In contrast, at 10^{-8} M DX, the accumulation of Cer was larger and followed by a smaller conversion into SP. Interestingly, the apoptotic effect of DX was weaker in the latter conditions, suggesting that DX mediates thymocyte death through SP generation rather than Cer accumulation. D-MAPP and NOE, Cerase inhibitors, prevented the generation of SP in response to DX, and although they increased Cer accumulation, they drastically reduced apoptosis, again arguing in favor of a role of SP, rather than Cer, in DX-mediated cell death. Furthermore, exogenous SP, or inhibition of SP kinase by DMS, induced thymocyte apoptosis, as reported in some cell types (11, 14). Additionally, whereas both exogenous aSMase and nSMase triggered apoptosis and the generation of Cer, only aSMase was able to increase SP level and aSMase-mediated apoptosis was strongly reduced by Cerase inhibition. Thus, it is likely that aSMase mediates apoptosis, at least in part, through SP production and aSMase-mediated apoptosis is strongly reduced by Cerase inhibition. Consequently, Cer and SP appear to be independent apoptotic messengers in thymocytes, as previously reported in cancer cells of different origins (40). However, our data reveal an unappreciated role of SP in glucocorticoid-induced thymocyte apoptosis.

DX-induced Cer and SP production appeared to be dependent on caspase activation. Early caspase-8 activation, via FADD-procaspase complexes, has been involved in aSMase activation in T cells after CD95 ligation (5, 17, 18, 41). Furthermore, CD95 clustering and recruitment of FADD-procaspase-8 complexes, independently of CD95 ligation, have been reported following anticancer drug treatment or hypoxia/serum deprivation (42, 43). Interestingly, in thymocytes, glucocorticoids promote the formation of FADD-procaspase-8 complexes (16). However, this mechanism could not account for caspase-8 activation upstream of aSMase, because the formation of FADD-procaspase-8 complexes, as well as caspase-8 activation, occurred later than the lipid.
generation (Refs. 6 and 16, and present data). Moreover, disruption of rafts with methyl-β-cyclodextrin, which strongly inhibits CD95 clustering and CD95-mediated thymocyte death (19), only marginally reduced DX-induced apoptosis (S. Lépine and F. Giraud, unpublished data). At present, the identity and the activation mechanism of the caspase responsible for aSMase activation upon DX stimulation remain unknown. However, recent studies suggest a role for the Src kinase, p56lc, in caspase activation and apoptosis (44, 45). Interestingly, in thymocytes, DX-induced apoptosis is mediated through the activation of an unknown Src kinase (16). Therefore, it could be possible that DX induced early caspase activation through the stimulation of p56lc. The target of this caspase could be aSMase itself, one of its upstream regulators (Src kinase, phospholipase C (16)) or a protein that negatively couples to one of these enzymes. In fact, it is not known whether the Src kinase acts upstream or downstream of the early caspases.

The present study provides evidence that SP is mediating the activation of caspase-8-3 through a mitochondria-independent pathway in DX-stimulated thymocytes. Indeed, blockade of SP production with Cerase inhibitors resulted in the impairment of caspase-8 and -3 processing, without affecting Δψm, loss or caspase-9 activation. A role for caspase-8 upstream of mitochondria, in DX-stimulated thymocytes, was proposed recently, because cytochrome c release was shown to be inhibited by a caspase-8 inhibitor, Z-IETD (16). However, cytochrome c release can be achieved in a caspase-dependent, via caspase-8 cleavage of Bid in CD95 (type II cells) and TNF-initiated cell death, or caspase-independent manner with other death-promoting stimuli (39). As Bid is not translocated to mitochondria after DX treatment of thymocytes (23), it seems unlikely that caspase-8 could mediate mitochondrial damage. Consistent with this latter conclusion, we show that Z-IETD was unable to inhibit DX-induced Δψm loss. Z-DEVD and Z-LEHD, inhibitors of caspase-3 and -9, respectively, did not alter DX-induced Δψm loss either, indicating that caspase-8, -3, and -9 are activated downstream and/or independently of mitochondria.

In thymocytes stimulated with the glucocorticoid, inhibition of Δψm loss, by BA or by blocking proteasome activity, was shown to prevent cytochrome c release and to abolish or to reduce caspase-3 activation (23, 24, 26). In the present study, we show that blocking Δψm loss through inhibition of either PTP by BA, or proteasome activity by MG132, abolished only caspase-9 processing, indicating that the proteasome/mitochondria pathway is responsible for caspase-9 activation, presumably through the apoptosome complex, initiated by cytochrome c release from mitochondria (46). However, in contrast to the results of Yoshino et al. (23), we have not observed—with thymocytes from a different mouse strain and a lower BA concentration—any inhibition of caspase-3 by BA, although caspase-9 was inhibited. Our data suggest that activation of caspase-3 did not result from upstream activation of caspase-9, but rather of caspase-8. In support of this conclusion, we found that caspase-8 and -3 activation was absolutely required for thymocyte apoptosis induced by DX, whereas caspase-9 was dispensable. The fact that BA inhibited DX-induced apoptosis could result from the blockade of mitochondrial release of apoptogenic proteins, other than cytochrome c, mediating activation of an unknown factor downstream of caspase-3 (47). In contrast to BA, MG132 reduced caspase-8 and -3 processing, indicating that proteasome activity is involved, as well as SP, in caspase-8-3 activation independently of mitochondrial alterations. FLIP has been identified as a blocker of apoptosis induced by TNF family death receptors (47). FLIP binds to CD95-FADD complex, inhibiting the recruitment and activation of caspase-8 (formerly known as FLICE). Interestingly, down-regulation of FLIP was shown to be mediated through ubiquitin/proteasome pathway (48), raising the possibility that DX-induced thymocyte apoptosis could be mediated through a proteasome-dependent caspase-8 activation. Additionally, proteasome activity could indirectly control caspase-9 and -3 processing, independently of mitochondria, through members of the inhibitor of apoptosis (IAP) family (XIAP and cIAP1), which are direct inhibitors of caspase-9 and -3 (49), capable of autoubiquitination and undergoing proteasome-dependent degradation in DX-treated thymocytes (50). Because DX-induced sphingolipid production is not dependent on proteasome activity, it appears that both SP and proteasome activity are controlling the caspase-8-3 cascade. This interpretation is consistent with the finding that apoptosis was partially reduced by inhibitors of either sphingolipid metabolism or proteasome activity. In contrast, inhibitors of caspase-8 and -3 totally abolished apoptosis, confirming that these caspases are activated downstream from sphingolipid and proteasome in the apoptotic cascade.

In conclusion, our study indicates that DX induces thymocyte apoptosis through different pathways (Fig. 7). One, mediated by caspase-dependent SP generation through the sequential activation of aSMase and Cerases, contributes to the activation of the caspase-8-3 cascade independently of the proteasome/mitochondria pathway. In parallel, independently of SP production, the activation of the caspase-8-3 cascade also depends on proteasome activity. A third pathway mediating apoptosis involves proteasome-dependent mitochondrial alterations, although by a mechanism independent of caspase-9 processing.

Acknowledgments

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