Krabbe disease: psychosine-mediated activation of phospholipase A2 in oligodendrocyte cell death

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Abstract Globoid cell leukodystrophy (Krabbe disease) is an inherited neurological disorder caused by the pathogenic accumulation of psychosine (galactosylsphingosine), a substrate for the deficient enzyme galactocerebrosidase β-galactosidase. This study underscores the mechanism of action of psychosine in the regulation of oligodendrocyte cell death via the generation of lysophosphatidylcholine (LPC) and arachidonic acid (AA) by the activation of secretory phospholipase A2 (sPLA2). There was a significant increase in the level of LPC, indicating a phospholipase A2 (PLA2)-dependent pathobiology, in the brains of Krabbe disease patients and those of twitcher mice, an animal model of Krabbe disease. In vitro studies of the treatment of primary oligodendrocytes and the oligodendrocyte MO3.13 cell line with psychosine also showed the generation of LPC and the release of AA in a dose- and time-dependent manner, indicating psychosine-induced activation of PLA2. Studies with various pharmacological inhibitors of cytosolic phospholipase A2 and sPLA2 and psychosine-mediated induction of sPLA2 enzymatic activity in media supernatant suggest that psychosine-induced release of AA and generation of LPC is mainly contributed by sPLA2. An inhibitor of sPLA2, 7,7-dimethyl eicosadienoic acid, completely attenuated the psychosine-mediated accumulation of LPC levels, release of AA, and generation of reactive oxygen species, and blocked oligodendrocyte cell death, as evident from cell survival, DNA fragmentation, and caspase-3 activity assays. This study documents for the first time that psychosine-induced cell death is mediated via the sPLA2 signaling pathway and that inhibitors of sPLA2 may hold a therapeutic potential for protection against oligodendrocyte cell death and resulting demyelination in Krabbe disease.—Giri, S., M. Khan, R. Rattan, I. Singh, and A. K. Singh. Krabbe disease: psychosine-mediated activation of phospholipase A2 in oligodendrocyte cell death. J. Lipid Res. 2006. 47: 1478–1492.

Supplementary key words twitcher • apoptosis • sPLA2 inhibitor • LPC

Krabbe disease, also known as globoid cell leukodystrophy, is an inherited demyelinating disease caused by a deficiency of galactosylceramidase. Cytotoxicity of psychosine in vitro and the fatal effects of intracranial-injected psychosine led to the conclusion (known as the psychosine hypothesis) that progressive accumulation of psychosine is the critical biochemical pathogenetic mechanism of cell death in Krabbe brain (1). There is accumulation of two substances, β-galactocerebroside, which accumulates within macrophages to form the characteristic globoid cells, and galactosylsphingosine (psychosine) (2). Galactocerebrosidase degrades β-galactocerebroside and psychosine into cerebroside and galactose and sphingosine and galactose, respectively. The galactocerebrosides are also hydrolyzed by GM1 gangliosidase, but it cannot degrade psychosine; therefore, there is enhanced accumulation of psychosine relative to galactocerebrosides (3). Loss of oligodendrocytes, the cells responsible for myelin formation, results in demyelination (2). Psychosine has been shown to induce several responses characteristic of Krabbe disease; for example, psychosine causes oligodendrocyte cell death (4–6), astrocyte activation (7), and the formation of multinuclear globoid-like cells in U937 monocytic cells (8) and NK cells (9). Apoptotic cells and expression of apoptotic-related molecules such as tumor necrosis factor-α (TNFα) have been observed in brains of the twitcher mouse, an animal model of Krabbe disease, and in brains of patients with Krabbe disease, leading to the conclusion that progressive accumulation of psychosine is the critical biochemical pathogenetic mechanism of cell death in the Krabbe brain (5, 6, 10). We have recently reported that psychosine
mediates oligodendrocyte cell death via upregulation of reactive oxygen species (ROS)-JNK-AP-1, a pro-apoptotic pathway, and downregulation of the NF-κB pathway, an antiapoptotic pathway (4). However, the mechanism of action of psychosine in the pathophysiology of Krabbe disease is not completely understood.

The observed expression of inflammatory mediators such as TNFα, IL-6, and iNOS in the central nervous systems (CNSs) of Krabbe disease patients and in twitcher mice indicates that the inflammatory response may play a role in the pathobiology of Krabbe disease (7, 10). Inflammatory cytokines are known to induce the phospholipase A2 (PLA2) enzyme system. PLA2s hydrolyze phospholipids at the sn-2 position to liberate AA (11). These mediators are critically involved in the regulation of several physiological events, including cell death (11, 12). The PLA2s have been divided into three major groups based on size, ability to be secreted, and calcium dependency (11). The three groups consist of low-molecular-mass sPLA2, (13.5–16.8 kDa), calcium-independent phospholipase A2 (iPLA2, 80 kDa), and high-molecular-mass cytosolic phospholipase A2 (cPLA2, 85 kDa) (11). The cPLA2, when activated by phosphorylation via an increase in the cytosolic concentration of calcium, translocates from the cytosol to either the nuclear membrane, endoplasmatic reticulum, Golgi, or plasma membrane, depending on cell type and stimulus (12–15), to catalyze the hydrolysis of membrane glycerophospholipids at the sn-2 position to liberate AA (11). Several mammalian intracellular and sPLA2s have been described previously (16). Among sPLA2s, type IIA sPLA2, also referred to as synovial PLA2, is a pro-inflammatory enzyme found to be highly elevated, both in the circulation and locally in the tissue, in a number of pathological diseases, such as atherosclerosis, asthma, and acute lung injury (17–19). Additionally, the identity and role of several sPLA2s is yet to be revealed.

The products of PLA2, i.e., lysophosphatidylcholine (LPC) and AA are bioactive lipids and are known to regulate a number of physiological and pathological events (11, 12). LPCs have been shown to induce demyelination (20, 21) by activating cell death in mature oligodendrocytes and in oligodendrocyte progenitors (22, 23). On the other hand, metabolism of AA gives rise to ROS, which induce oxidative stress, leading to either cell proliferation or apoptosis, depending on the cell type (24–27) and also regulate redox-sensitive transcription factors AP-1 and NF-κB by activating p38 mitogen-activated protein kinase (MAPK) (28–30). Released free AA either acts as a second messenger or is further metabolized by three different enzyme systems, i.e., cyclooxygenase, lipooxygenase, and cytochrome P450 epoxygenase, to generate eicosanoid signaling molecules, including prostaglandins, leukotrienes, and thromboxanes (31). These, in turn, may set the stage for augmented synthesis of lipid mediators, free radicals, and ROS, and hence peroxidative and oxidative damage to cellular membranes (32, 33).

The present study was undertaken to gain a better understanding of the underlying mechanisms of psychosine-induced apoptosis of oligodendrocytes. Studies reported here document excessive accumulation of LPC in brains of twitcher mice and of Krabbe disease patients, indicating a possible role of PLA2 in the pathobiology of Krabbe disease. Activation of psychosine-mediated sPLA2 activity and inhibition of psychosine-induced cell death by the inhibitor of sPLA2 demonstrate that the sPLA2-mediated signal transduction pathway plays a critical role in the psychosine-induced cell death of oligodendrocytes and that these effects of psychosine are independent of TDAG8, a presumed receptor for psychosine. The inhibition of psychosine-induced cell death by the inhibitor of sPLA2 indicates that psychosine mediates its proapoptotic signaling through the PLA2 pathway rather than as the originally suggested consequence of its lytic activity (psychosine hypothesis) (1).

MATERIALS AND METHODS

Reagents

DMEM/4.5 gm glucose/L medium, fetal bovine serum, and Hank’s balanced salt solution were obtained from Life Technologies (Grand Island, NY). N-[(2S,4R)-1-{(biphenyl-2-ylmethyl)-isobutyl-amino}-1-[2(4-difluorobenzoyl)-benzoyl]-pyrrolidin-2-ylmethyl]-3-[2(4-dioxothiazolidin-5-ylidenemethyl)-phenyl]acrylamide (BDDPAA), arachidonyl trifluoromethyl ketone (AOCOF3), c(2NapA)LS(2NapA)R, TFA (NNTFA), 7,7-dimethyl eicosadienoic acid (DEDAA), were purchased from EMD Biosciences, Inc. (San Diego, CA) and antibodies against p-cPLA2, p-p38, and p-JNK were purchased from Cell Signaling Technology (Beverly, MA). 6-Carboxy 2’, 7’-dichlorodihydroflourescein diacetate (DCFDA) was from Molecular Probes (Eugene, OR). Lipofectamine 2000 was from Invitrogen. Antibodies against TDAG8 were from Santa Cruz Biotechnology (Santa Cruz, CA). Psychosine, gluco-psychosine, ceramide, and sphingosine were from Matreya (Pleasant Gap, PA). MO3.13 oligodendroglial cells were a kind gift from Dr. Catherine Waters (Division of Neuroscience, Biological Sciences, University of Manchester, UK). The expression vector for TDAG8 was a kind gift from Dr. Kevin R. Lynch (University of Virginia School of Medicine, Charlottesville, Virginia).

Cell culture

Rat primary oligodendrocytes were prepared in our laboratory as described previously (34). The cells were maintained in DMEM (4.5 gm glucose/l) containing 10% FBS and 10 μg/ml gentamicin. All cultured cells were maintained at 37°C in 5% CO2/95% air. At 80% confluency, the cells were incubated with serum-free DMEM medium for 24 h prior to incubation with various treatments. MO3.13 oligodendroglial cells were maintained in DMEM (4.5 gm glucose/l) containing 10% FBS and 10 μg/ml gentamicin. This oligodendrocyte cell line was maintained under serum-free conditions for 24 h before treatment. It was observed that such serum-free conditions led to the expression of the oligodendrocyte marker GST-π in these cells. Psychosine was first dissolved in DMSO and then mixed in the medium at a DMSO concentration 0.1% of the medium.

Human autopsy brain specimens

Frozen-fixed tissues of two Krabbe-diseased brains and two normal age-matched controls were from the Brain and Tissue
Bank (University of Maryland at Baltimore, MD). The frozen-fixed tissues were processed for LPC analysis as described below. Sections from normal brains were cut from corresponding anatomical locations.

Animals

All animal work was approved and performed according to the Guidelines for the Care and Use of Laboratory Animals according to the recommendations of the Institutional Animal Care and Use Committee of the Medical University of South Carolina (MUSC). Twitcher heterozygote breeding pairs (C57BL/6J twi/+) were purchased from Jackson Laboratory (Bar Harbor, ME) and maintained at MUSC’s animal facility. The genotypes of all newborns were determined according to the PCR-based method described by Sakai et al. (36) with modifications (suggested by N. Sakai, personal communication) using DNA isolated from tails of 7- to 8-day-old pups (35). We used 5′-GAGAATATGGTGTGTTGGAATGGTTTTGC-3′ (25 mCi/mmol) overnight at 37°C and 1480 Journal of Lipid Research Volume 47, 2006

Measurement of ROS

ROS were determined using the membrane-permeable fluorescent dye 5-carboxy-2′,7′-dichlorodihydrofluorescein (DCFCA) diacetate in serum-free medium as described previously (39). The cultured cells, with or without treatment, were incubated with 5 μM DCF dye in PBS for 2 h at 37°C. The change in fluorescence was determined at excitation 485 nm and emission 530 nm using a Soft Max Pro spectrofluorometer (Molecular Devices, Sunnyvale, CA).

3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT) assay for cell growth and viability

The viability of cells was evaluated using the MTT assay. This assay is based on the cleavage of tetrazolium salt MTT to a dark blue formazan product by mitochondrial dehydrogenase in viable cells. The absorbance of viable cells was measured with a test wavelength of 570 nm and a reference wavelength of 630 nm.

DNA fragmentation

After treatment, cells were harvested and then lysed with lysis buffer containing 20 mM NaCl, 10 mM Tris-HCl (pH 8.0), 25 mM EDTA, 1% sodium dodecyl sulfate, and 1 mg/ml proteinase K for 24 h in a 55°C water bath. The standard phenol-chloroform-isoamyl alcohol method (25:24:1) was used to remove protein and extract nucleic acid. RNA was digested with RNase A (100 μg/ml) for 12 h at 37°C, and DNA concentrations were determined. DNA extracts were electrophoresed on a 2% agarose gel at 50 V for 45 min and visualized with ethidium bromide staining under ultraviolet illumination (40).

Transfection studies

Plasmids were purified using the endotoxin-free plasmid midi prep kit (Qiagen). For transient transfections, HEK293 cells were seeded in 6-well plates and grown to 60–80% confluence in DMEM/F-12 plus 5% FBS without antibiotics and transfected using Lipofectamine 2000 reagent. TDAG8 expression vector (1–3 μg), along with insertless expression vector (pcDNA3.1), was used for transfecting. Cells were treated with psychosine and/or DEDA for 24 h and processed for further experiments. For PathDetect® in Vivo Signal Transduction Pathway trans-Reporting Systems (Stratagene; La Jolla, CA), MO3.13 cells were transiently transfected with 0.5 μg pFA2-Jun-Gal4, pFA2-EIk1-Gal4, or pFA2-CHOP-Gal4 DNA binding domain, along with 0.5 μg pFR-chloramphenicol acetyltransferase (pFR-CAT) reporter, using Lipofectamine 2000 reagent. After 24 h of transfection, cells were treated with DEDA and psychosine for 24 h and processed for CAT by ELISA (Roche). pFC-MEKK (for JNK), pFC-MEK1 (for p42/44), and pFC-MEK3 (for p38) were
cotransfected, followed by phorbol 12-myristate 13-acetate (PMA) (0.1 nM) treatment as a positive control. pCMV-GAL4 binding domain (without insert) and pFR-CAT were transfected as a control to detect the basal levels of CAT activity.

**Short interfering RNA experiments**

To decrease the levels of endogenous TDAG8, MO3.13 cells were transfected for 48 h with 25 nM of short interfering RNA (SiRNA) of TDAG8 or control (Santa Cruz Biotechnology). SiRNAs were transfected with Lipofectamine 2000 reagent according to the manufacturer’s instructions. The cells were then treated with psychosine for 8 h or 24 h for AA release or for caspase 3 activity assay, respectively.

**Activation of caspase 3**

Caspase 3 activation was determined using substrates [acetyl-Asp-Glu-Val-Asp (Ac-DEVD)-7-amino-4-methyl-coumarin (AMC) for caspase 3 procured from Biomol (Plymouth Meeting, PA)], which are cleaved into fluorescent reaction products by the respective caspase activity (40). For analysis of caspase 3 activity, cells were collected and lysed in 100 µl of lysis buffer containing 10 mM Tris-HCl, pH 7.5, 130 mM NaCl, 1% (w/v) Triton X-100, and 10 mM sodium pyrophosphate. The lysate was incubated with 20 µm substrate in reaction buffer [20 mM HEPES-10% (v/v) glycerol-2 mm dithiothreitol] at 37°C for 15 min. The fluorescence intensity (expressed as arbitrary U/µg protein) of liberated AMC was measured using spectrophotometer (excitation wavelength, 380 nm; emission wavelength, 460 nm).

**Western blot analysis**

Western blot analysis for phospho-MAPKs, cPLA2, and TDAG8 was performed using standard procedures. Cells were harvested and lysed with lysis buffer [50 mM Tris-HCl (pH 7.5), 250 mM NaCl, 5 mM EDTA, 50 mM NaF, and 0.5% Nonidet P-40] containing a protease inhibitor cocktail (Sigma). The lysate was clarified by centrifugation at 10,000 g for 15 min at 4°C. Equal amounts of total protein (50 µg) were subjected to 4–20% SDS-PAGE and electrophoretically transferred to a High-Bond nitrocellulose membrane (Amersham Life Science; Arlington Heights, IL). After blocking with Tween 20-Tris-buffered saline (TTBS; 20 mM Tris-HCl (pH 7.6), 137 mM NaCl, and 0.05% Tween 20) containing 5% nonfat milk for 1 h at room temperature, the membranes were incubated overnight at 4°C with the primary antibodies at 1:1,000 dilution in blocking buffer (TTBS with 5% nonfat milk). The membranes were then washed three times for 10 min each in TTBS and incubated with an appropriately diluted horseradish peroxidase-labeled secondary antibody (1:5,000) in blocking buffer for 1 h at room temperature. The membranes were washed three times, reacted with ECL reagent (Amersham Life Science), and subjected to autoradiography.

**Statistical analysis**

Data are expressed as mean ± SD for n experiments. Statistical comparisons were made using one-way ANOVA followed by Student’s t-test and Student Newman-Keuls test as required. A P value <0.05 was considered statistically significant.

**RESULTS**

**Accumulation of LPC in Krabbe and twitcher brain**

The lipid composition of Krabbe and twitcher brains was analyzed, and a significant increase in the levels of LPC in the Krabbe and twitcher brains was observed (Fig. 1A, B). To examine the possibility that elevated levels of psychosine in Krabbe and twitcher brain are responsible for LPC generation, primary oligodendrocytes were treated with different concentrations of psychosine (5–20 µM). It was observed that psychosine treatment significantly increased the LPC levels in a dose-dependent manner in primary oligodendrocytes. A similar pattern was also observed in the oligodendrocyte cell line MO3.13 (Fig. 1C, D). These observations indicate that psychosine accumulation due to a genetic defect causes excessive accumulation of LPC in both Krabbe patient and twitcher mouse brains as well as in cells treated with psychosine.

**Psychosine-induced AA release in primary oligodendrocytes and the MO3.13 cell line**

To further evaluate the psychosine-mediated generation of LPC, the effect of psychosine on the hydrolysis of phospholipids was investigated. For this, primary oligodendrocytes were labeled with radioactive [14C]AA. After 12 h of incubation, cells were washed with media three times, followed by treatment with different concentrations of psychosine (5–40 µM). As depicted in Fig. 2A, in primary oligodendrocyte cells treated with psychosine, there was a significant release of labeled AA. A similar trend was observed when the oligodendrocyte cell line MO3.13 was used (Fig. 2B). Psychosine treatment induced sPLA2 activity in media supernatant in a dose- and time-dependent manner (Fig. 2C). Like psychosine (galactopsychosine), glucopsychosine was equally potent in inducing AA release, whereas ceramide and sphingosine had no effect on MO3.13 cells (Fig. 2D), documenting the specificity of the AA-releasing activity of psychosine and glucopsychosine in oligodendrocytes.

**Psychosine-induced AA release is dependent on cPLA2 and sPLA2**

To investigate the enzymatic activity responsible for the psychosine-induced AA release that is dependent on cPLA2 and sPLA2, we employed specific pharmacological inhibitors of cPLA2 and sPLA2. Treatment with BDDPAA and AACOF3 (cPLA2 inhibitor) at different concentrations (5–20 µM) significantly inhibited psychosine-induced AA release in MO3.13 cells, suggesting the possible role of cPLA2 in psychosine-mediated AA release (Fig. 3A). Because we did not observe complete inhibition of AA release mediated by psychosine, the role of sPLA2 was also examined using its specific inhibitors, NNTFA and DEDA. For this, MO3.13 cells were treated with NNTFA and DEDA for 30 min prior to the addition of psychosine. After 8 h of treatment, release of labeled AA in supernatant was examined. Inhibitors of sPLA2 significantly inhibited the psychosine-induced AA release, indicating the role of sPLA2 (Fig. 3B). We also used a combination of suboptimal doses of the cPLA2 inhibitor (BDDPAA, 10 µM) and the sPLA2 inhibitor (DED, 5 µM) and examined the effect on psychosine-mediated AA release. The combination of suboptimal doses of BDDPAA (10 µM) and DEDA (5 µM) inhibitors further significantly inhibited the psychosine-induced AA release (Fig. 3C), indicating that both cPLA2
and sPLA2 are involved in the psychosine-mediated release of AA in oligodendrocyte cells.

DEDA inhibits psychosine-induced LPC generation in the oligodendrocyte cell line

To investigate the relationship of AA release and generation of LPC, the generation of LPC was examined in MO3.13 cells treated with DEDA followed by psychosine. After 8 h of treatment with psychosine in the presence or absence of DEDA, cells were processed for LPC detection as described in Materials and Methods. It was observed that the sPLA2 inhibitor (DEDA) completely blocked LPC generation (Fig. 4). However, the cPLA2 inhibitor (BDDPAA) had no effect on LPC generation induced by psychosine (data not shown). The observed complete attenuation of psychosine-induced generation of AA and LPC by the sPLA2 inhibitor as compared with the cPLA2 inhibitor indicates that sPLA2 activity plays a prominent role in this process.

DEDA blocked psychosine-mediated induction of MAPKs in oligodendrocytes

MAPKs such as ERK p42/p44, JNK/SAPK, and p38 of the MAPK pathway have been implicated in the regulation of the signaling pathways leading to apoptosis in response to oxidative stress. To examine the effect of DEDA on the psychosine-mediated induction of MAPKs (p42/44, JNK, and p38), MO3.13 cells were treated with DEDA (10 μM) in the presence or absence of psychosine (20 μM). After 30 min of incubation, cells were processed for the phosphor status of these MAPKs using immunoblot analysis. As shown in Fig. 5A, psychosine induced the phosphorylation of p42/44, JNK, and p38 and also induced the phosphorylation of cPLA2. Treatment with DEDA blocked the psychosine-induced phosphorylation of these MAPKs and cPLA2. This observation was further confirmed using PathDetect® in Vivo Signal Transduction Pathway trans-Reporting Systems (Stratagene; La Jolla, CA). For this, cells were cotransfected with the fusion transactivator plasmid [c-Jun (for JNK), Elk1 (for p42/44), or CHOP (for p38) transcriptional activator fused with the yeast GAL4 DNA binding domain residues 1-147] and reporter plasmid (CAT) and then treated with DEDA in the presence or absence of psychosine. After 24 h incubation, cells were processed to examine the expression of CAT as a reporter using a CAT ELISA kit (Roche Applied Science; Indianapolis, IN). CAT expression from the reporter plasmid in response to psychosine treatment indicated the activation of the fusion transactivator protein and, therefore, the activation of the endogenous protein kinase.
(ERK p42/p44, JNK/SAPK, and p38) (Fig. 5B). Treatment with DEDA in these transfected cells significantly blocked the in vivo activation of these MAPKs.

**Psychosine-induced AA release by ROS generation**

Psychosine has been shown to induce oxidative stress and to regulate peroxisomal functions and apoptosis in primary oligodendrocytes and the MO3.13 cell line (4, 39). As reported earlier, psychosine treatment induced ROS generation in a dose- and time-dependent manner (Fig. 6A, B).

Glucopsychosine was observed to be more potent in inducing ROS generation in MO3.13 cells as compared with psychosine, whereas, ceramide and sphingosine had no effect (Fig. 6C). To investigate whether ROS plays any role in AA release, we examined the effect of antioxidant [N-acetylcysteine, (NAC)] on AA release. Treatment with NAC completely blocked psychosine-induced ROS generation (Fig. 6D) and also inhibited AA release and LPC generation (Fig. 6E, F), documenting that oxidative stress plays a role in the observed psychosine-mediated effects. We have
previously reported that treatment with NAC attenuated psychosine-induced cell death in oligodendrocytes (4). Because DEDA inhibited psychosine-mediated generation of AA and LPC, it was of interest to examine the effect of DEDA on psychosine-mediated induction of ROS. For this, cells were treated with different concentrations of DEDA (5–20 μM), and ROS was measured in psychosine- and DEDA-treated cells. As depicted in Fig. 6G, the sPLA2 inhibitor (DEDA), but not the cPLA2 inhibitor (BDDPAA), inhibited the psychosine-induced ROS generation.

**Fig. 4.** DEDA inhibits the psychosine-mediated accumulation of LPC. MO3.13 cells were treated with different concentrations of DEDA for 30 min, followed by psychosine treatment. After 8 h of incubation, cells were processed for LPC measurement as described in Materials and Methods. Results are mean ± SD of three determinations. ### $P < 0.001$ as compared with untreated cells. **$P < 0.01$ and *** $P < 0.001$ as compared with psychosine-treated cells. NS, not significant as compared with untreated cells.

**Fig. 3.** Effect of cytosolic phospholipase A2 (cPLA2) and sPLA2 inhibitors on psychosine-mediated release of AA. A: MO3.13 cells were labeled with [3H]AA as described in Materials and Methods. Cells were treated with different concentrations (5–20 μM) of cPLA2 inhibitors (BDDPAA and AACOF3) for 30 min, followed by psychosine treatment. After 8 h, radioactivity released in the medium (100 μl) was measured. ### $P < 0.001$ as compared with untreated cells; * $P < 0.05$ and *** $P < 0.001$ as compared with psychosine-treated cells. NS, not significant. B: Cells were treated with different concentrations (5–20 μM) of sPLA2 inhibitors (DEDA and NNTPA) for 30 min after labeling with labeled AA, followed by psychosine treatment for 8 h and counting of radioactivity. ### $P < 0.001$ as compared with untreated cells; * $P < 0.05$ and *** $P < 0.001$ as compared with psychosine-treated cells. NS, not significant. C: Labeled MO3.13 cells were treated with BDDPAA (10 μM) and DEDA (5 μM), followed by psychosine treatment for 8 h; this was followed by radioactivity counting in media. ### $P < 0.001$ as compared with untreated cells; ** $P < 0.01$ and *** $P < 0.001$ as compared with psychosine-treated cells; @ $P < 0.001$ and & $P < 0.01$ as compared with psychosine/BDDPAA- and psychosine/DEDA-treated cells, respectively.

**Fig. 5.** Effect of N-acetylcysteine (NAC) on psychosine-induced oligodendrocyte cell death

Loss of oligodendrocytes is a hallmark in demyelinating Krabbe disease, and progressive accumulation of psychosine has been implicated in oligodendrocyte cell death in vivo and in vitro. Because the sPLA2 inhibitor attenuated AA release and LPC generation, we further examined its effect on psychosine-induced oligodendrocyte cell death. For this, MO3.13 cells were treated with DEDA and the cPLA2 inhibitor BDDPAA for 30 min, followed by psychosine (20 μM) treatment. After 48 h, MTT was performed to detect cell survival. As reported previously, psychosine at a concentration of 20 μM induced cell death significantly (4). The sPLA2 inhibitor blocked the psychosine-mediated cell death, whereas the cPLA2 inhibitor BDDPAA had no effect (Fig. 7A, B), documenting the role of sPLA2 in psychosine-induced cell death. This observation was further supported by morphologic analysis, DNA fragmentation, and caspase 3 activity assays. As evident from morphologic analysis, MO3.13 cells treated with psychosine detached from the plate. However, their detachment was completely blocked when they were treated with DEDA (Fig. 7C). To examine the effect of DEDA on psychosine-mediated DNA fragmentation, cytoplasmic DNA isolated from cells treated in a similar manner was subjected to agarose gel electrophoresis (Fig. 7C). A DNA ladder was observed in cells treated with psychosine but not in control cells, and this ladder was reduced by the treatment with DEDA at 5 μM and 10 μM concentrations at 48 h of treatment. DEDA treat-
ment also attenuated psychosine-induced caspase 3 activity in the oligodendrocyte cell line (Fig. 7D). Taken together, these studies document that the sPLA2 inhibitor DEDA inhibits psychosine-induced oligodendrocyte cell death.

**Psychosine-mediated effect is independent of TDAG8 receptor**

TDAG8, a G protein-coupled receptor, has been proposed to be the receptor for the psychosine effect (41). To examine whether the psychosine-mediated effects are dependent on its receptor, the effect of SiRNA for TDAG8 was investigated on psychosine-induced AA release and caspase 3 activity. As depicted in Fig. 8A, psychosine treatment induced AA release; however, transfection with SiRNA of TDAG8 did not alter the psychosine-mediated AA or caspase 3 activity (Fig. 8B). However, TDAG8 SiRNA transfection was able to reduce the approximately 50% levels of endogenous TDAG8 in MO3.13 cells (Fig. 8A, inset). To confirm further the TDAG8-independent effects of psychosine, we employed the HEK293 cell line, which is deficient for TDAG8, to study psychosine effects (41). For this, HEK293 cells labeled with [14C]AA were treated with different concentrations of psychosine (5–30 μM). In agreement with studies on primary oligodendrocytes and MO3.13 cells, psychosine treatment induced the release of labeled AA in media in a dose-dependent manner (Fig. 8C), suggesting that the psychosine-mediated effect on AA release is independent of the TDAG8 receptor. Moreover, psychosine also induced LPC generation in HEK293 cells (Fig. 8D). To further support these observations, we transfected HEK293 cells with a mammalian expression vector of TDAG8, followed by the
Fig. 6. Oxidative stress plays an important role in psychosine-mediated effects in the oligodendrocyte cell line. A: MO3.13 cells were treated for 60 min with different concentrations of psychosine (5–30 μM) in the presence of 6-carboxy 2',7'-dichlorodihydrofluorescein diacetate (DCFDA) dye, and fluorescence was recorded as described in Material and Methods. Data are the mean of three values ± SD. ** P < 0.01 and *** P < 0.001 as compared with untreated cells. B: MO3.13 cells were treated with psychosine (20 μM) for various time periods (10–60 min) in the presence of DCFDA dye followed by fluorescence measurement. Data are the mean of three values ± SD. NS, not significant; ** P < 0.01 and *** P < 0.001 as compared with untreated cells. C: MO3.13 cells were treated with 20 μM concentrations of psychosine, glucopsychosine, ceramide, and sphingosine for 60 min in the presence of DCFDA dye, followed by fluorescence measurement. Results are mean ± SD of three determinations. NS, not significant; *** P < 0.001 as compared with untreated cells. D: MO3.13 cells were pretreated with N-acetylcysteine (NAC) for 2 h followed by psychosine- or glucopsychosine-treated cells for 60 min in the presence of DCFDA dye, followed by fluorescence measurement. Results are the mean ± SD of three determinations. NS, not significant; *** P < 0.001 as compared with untreated cells; ### P < 0.001 as compared with psychosine- or glucopsychosine-treated cells, respectively. E: To examine the effect of NAC on psychosine-induced AA release, MO3.13 cells were labeled with [3H]AA as described in Materials and Methods. After 12 h, cells were washed and treated with NAC for 2 h prior to the addition of psychosine for 8 h. Release of labeled AA in medium was counted as described in Materials and Methods. Results are the mean ± SD of three determinations. ** P < 0.01 as compared with untreated cells; ### P < 0.001 as compared with psychosine-treated cells. F: To examine the effect of psychosine- or glucopsychosine-treated cells, respectively. G: To examine the effect of DEDA on reactive oxygen species, MO3.13 cells were treated with DEDA and BDDPAA for 30 min prior to the addition of psychosine (20 μM) for 60 min in the presence of DCFDA dye, and fluorescence was recorded as described in Materials and Methods. Data are the mean of three values ± SD. *** P < 0.001 as compared with untreated cells; # P < 0.01, ### P < 0.001, and NS, not significant as compared with psychosine-treated cells.
AA-release assay. Transient transfection of the TDAG8 expression vector did not alter the psychosine-mediated release of AA (Fig. 8E). However, its transfection significantly induced the caspase 3 activity in these cells in both the presence and the absence of psychosine (Fig. 8F), which is in agreement with previous studies (42–44). Altogether, these sets of experiments clearly demonstrate that psychosine-mediated AA release and LPC generation is independent of TDAG8. These conclusions are in agreement with a very recent report using TDAG8 knock-out mice, which established that TDAG8 is not a receptor for psychosine (45). In summary, the results described in this study clearly document that psychosine induces cell death via the sPLA2-mediated signal transduction pathway, independent of TDAG8.

**DISCUSSION**

Progressive accumulation of psychosine, loss of oligodendrocytes, and demyelination are a hallmark of Krabbe disease; however, the mechanism of psychosine-induced loss of oligodendrocytes resulting in demyelination is not well understood (1, 2). In the present study, we have shown that the mechanism of action of psychosine-mediated oligodendrocyte cell death is via activation of sPLA2.
Fig. 8. The psychosine-mediated effect is independent of the TDAG8 receptor. A: To examine the role of TDAG8 in psychosine-mediated effects, MO3.13 cells were transfected with TDAG8 short interfering RNA (SiRNA) according to the manufacturer’s instructions. After 48 h, cells were labeled with [3H]AA as described previously. After 12 h, cells were washed and treated with psychosine for 8 h. Release of labeled AA in medium was counted as described in Materials and Methods. Results are the mean ± SD of three determinations. *** P < 0.001 as compared with control and TDAG8 SiRNA-untreated cells; NS, not significant as compared with psychosine-treated control SiRNA cells. To examine the effect of SiRNA on TDAG8 protein levels, cells were transfected with control and TDAG8 SiRNA, and cell lysate (50 μg) was used for immunoblot analysis for the detection of TDAG8 levels as described in Materials and Methods (inset). B: To examine the caspase 3 activity, cells were transfected with TDAG8 SiRNA as described previously, followed by psychosine treatment for 48 h and caspase 3 activity assay. Results are the mean ± SD of three determinations. *** P < 0.001 as compared with control and TDAG8 SiRNA-untreated cells; NS, not significant as compared with psychosine-treated control SiRNA cells. C: HEK293 cells were labeled with [3H]AA as described in Materials and Methods. After 12 h, cells were washed and treated with psychosine (5–30 μM) for 24 h. Release of labeled AA in the medium was counted as described in Materials and Methods. Data are the mean of six values ± SD. ** P < 0.01; *** P < 0.001; NS, not significant as compared with untreated cells. D: To examine the LPC accumulation, HEK293 cells were treated with psychosine (20 μM) for 24 h, followed by LPC detection as described in Materials and Methods. Data are the mean of three values ± SD. ** P < 0.01 as compared with untreated cells. E: HEK293 cells were transiently transfected with the expression vector of TDAG8 with Lipofectamine 2000 as described in Materials and Methods. After 24 h, cells were labeled with [3H]AA and treated with psychosine (20 μM). After 24 h, media was taken for radioactive counting. Results are the mean ± SD of three determinations. *** P < 0.001 as compared with pcDNA3- or TDAG8-transfected untreated cells; NS, not significant as compared with psychosine-treated pcDNA3-transfected cells. F: For caspase 3 activity, HEK293 cells were transfected with the expression vector of TDAG8 as described in Materials and Methods. After 48 h treatment with psychosine, the cell lysate was processed for caspase 3 activity assay. Results are the mean ± SD of three determinations. *** P < 0.001 as compared with pcDNA3-transfected untreated cells; and & P < 0.001 and # P < 0.001 as compared with psychosine-treated pcDNA3-transfected cells and TDAG8-transfected untreated cells, respectively.
and generation of LPC and AA. This conclusion is based on the following observations: i) Brains of Krabbe patients and twitcher mice exhibited significant accumulation of LPC. ii) Psychosine treatment significantly induced the generation of LPC and AA release in primary oligodendrocytes and the MO3.13 cell line. iii) Studies using various pharmacological inhibitors of cPLA2 and sPLA2 and enzymatic activation of sPLA2 activity document that psychosine-induced release of AA is contributed mainly by sPLA2. iv) The sPLA2 inhibitor DEDA completely attenuated psychosine-induced generation of LPC and AA. v) The sPLA2 inhibitor DEDA also inhibited the generation of ROS and oligodendrocyte cell death, as evident from cell survival, DNA fragmentation, and caspase 3 activity, and these effects of psychosine are independent of the presumed receptor of psychosine, TDAG8. Taken together, these results indicate that the sPLA2 inhibitor may have therapeutic potential, either alone or in combination with anti-inflammatory drugs for twitcher/Krabbe disease.

TDAG8 (T-cell death-associated gene 8) was initially cloned as an orphan G protein-coupled receptor, which was upregulated during the programmed cell death of T-lymphocytes (42–44). Im et al. (41) reported that TDAG8 is a putative receptor for psychosine and that its overexpression results in the formation of multinuclear cells by psychosine. Our results are in contrast with these observations. We observed that psychosine-mediated oligodendrocyte cell death is independent of TDAG8 in MO3.13 oligodendrocyte cells. In support of our finding, recently a study using TDAG8 knockout mice has also reported that psychosine-mediated effects are independent of TDAG8 (45). Moreover, psychosine-mediated effects were also observed in the HEK293 cell line, where TDAG8 expression is deficient (41), further suggesting that psychosine-mediated effects such as the AA release and LPC and ROS generation observed in oligodendrocytes and in the HEK293 cell line are independent of TDAG8. Overexpression of TDAG8 induces caspase 3 activity in the HEK293 cell line, which is consistent with a previous report in which its expression was upregulated during the programmed cell death of T-lymphocytes (42–44).

Several studies have reported a role for psychosine in regulating apoptotic cell death in Krabbe disease (4, 5, 46–49), yet its molecular mechanism(s) remain an enigma. While investigating the lipid composition of brains from Krabbe patients and from twitcher mice, we observed increased levels of LPC. In the present study, we have documented the possible role of LPC and AA generated by activation of sPLA2 in psychosine-mediated oligodendrocyte cell death. PLA2-mediated alterations of phospholipid metabolism have been suggested to be responsible for neurodegeneration in ischemia, spinal cord trauma, head injury, and Alzheimer’s disease (50). Under these pathological conditions, PLA2 may be involved in the massive release of AA and accumulation of eicosanoids. ROS generated during phospholipid degradation produce oxidative stress and are closely associated with the apoptotic as well as necrotic cell death that occurs in neurological disorders (50). We have documented recently that psychosine induces ROS generation and depletes GSH levels in twitcher mice and oligodendrocyte cells (4).

Inhibitors of cPLA2 (BDDPAA and AACOF3) partially inhibited the release of AA, whereas the sPLA2 inhibitor DEDA completely inhibited psychosine-induced oxidative stress, generation of AA and LPC, caspase 3 activity, and apoptotic cell death. DEDA is considered to be a specific inhibitor of sPLA2 over cPLA2 (51), but it is also a weak inhibitor of 5-lipoxygenase with a higher IC50 (56 μM), suggesting the possible involvement of 5-lipoxygenase, in addition to cPLA2 and sPLA2, in psychosine-mediated effects. We also observed that DEDA attenuated psychosine-mediated activation of p42/44 MAPK, stress MAPKs (p38 and JNKs), and phosphorylation of cPLA2. Therefore, the complete inhibition of AA release by DEDA may be due not only to direct inhibition of sPLA2 but also to the inhibition of cPLA2 phosphorylation via downregulation of p42/44 and p38, a critical for cPLA2 phosphorylation, membrane translocation, and it’s enzymatic activity (11, 12). Accordingly, DEDA treatment inhibited MAPK phosphorylation as well as phosphorylation of cPLA2. Our efforts to identify the sPLA2 involved in psychosine-mediated cell death have not been successful thus far. Moreover, the involvement of iPLA2 can also be ruled out, because a specific iPLA2 inhibitor, bromoenol lactone, did not affect the psychosine-mediated AA release in MO3.13 cells (data not shown). Studies are in progress to identify the sPLA2 specific for psychosine-induced signaling pathways.

A direct correlation between psychosine treatment and dose-dependent elevated levels of LPC generation and AA release in primary oligodendrocytes and MO3.13 cells suggests that increased levels of psychosine may be responsible for the higher levels of LPC found in Krabbe and twitcher brains. LPC is a well-known lysolipid, responsible for inducing demyelination in an animal model (20, 21) and cell death of mature oligodendrocytes and their progenitors in vitro (22, 23). The demyelinating effects of LPC are known to appear very rapidly in vitro as well as in vivo, and result from an increase in the hydrophilic nature of the molecular components of membranes, leading, in the case of myelin, to disruption of the intraperiod line, and finally to solubilization of the sheath (20). Elevated levels of psychosine elicit unique cellular reactions, such as formation of multinucleated cells (globoïd cells) from resident microglia/macrophages, and reactive astrogliosis (52, 53). Activated glial cells produce various inflammatory cytokines and related mediators (7, 10, 54) and chemokines, including macrophage chemoattractant protein-1, which are likely to play an important role in recruiting peripheral macrophages into the brain (54). These recruited macrophages further upregulate the inflammatory disease and participate in the progressive demyelinating disease process in Krabbe disease and in twitcher mice. LPC is known to act as a chemoattractant for monocytes (55) and T lymphocytes (56, 57) and also enhances the production of interferon-γ by activated T cells, thus promoting an inflammatory reaction (58, 59). Because elevated levels of LPC are observed in Krabbe and twitcher brain, it can be postulated that LPC may, at least
in part, be responsible for the inflammatory response observed in Krabbe disease and in twitcher mice. Moreover, LPC is also a precursor for platelet-activating factor, which is a well-known inflammatory mediator in the regulation of several inflammatory diseases (60–63). Therefore, inhibition of LPC generation should play an important part in therapeutics against the disease process in Krabbe disease and twitcher mice brains.

On the other hand, AA and its metabolites are important second messengers involved in the regulation of several biological processes, such as tissue inflammation and cell growth, differentiation, and apoptosis, through the activation of different signal transduction pathways (64–68), leading to the activation of transcription factors such as redox-sensitive transcription factors AP-1 and NF-κB by the activation of p38 MAPK (28–30). The metabolism of AA gives rise to ROS, which may induce oxidative stress leading to either cell proliferation or apoptosis, depending on the cell type (24–27). The inhibition of psychosine-induced cell death by the inhibitor of sPLA2 in oligodendrocytes indicates that LPC- and/or AA-mediated activation of signaling pathways is responsible for the loss of oligodendrocytes in Krabbe disease.

Due to variable forms of onset of clinical signs in patients with Krabbe disease and the lack of correlation between disease progression and enzyme levels or mutation status, other factors, such as environmental and/or other genetic factors, have been suggested to influence the late onset of Krabbe disease. Environmental factors include the possibility that trauma, i.e., a blow to the head (69) or viral infections (70, 71), may trigger the onset of symptoms in humans with Krabbe disease, perhaps by induction of proinflammatory mediators. Genetic factors include the presence of modifier genes that interact with the disease, causing gene or influence the disease process and, thus, impact disease progression. The saposin A and acid β-galactosidase genes are perfect examples of genetic factors, inasmuch as mutations in these genes can lead to a slowly progressive form of Krabbe disease in twitcher mice (72, 73). Similarly, a change in the genetic background of twitcher mice, from C57BL/6 to C57BL/6 × CAST/Ei background, significantly increases the life span (61.4 ± 2.5 vs. 37.0 ± 0.6 days), with fewer lectin-positive globoid cells, less gliosis, and a greater preservation of myelin, compared with C57BL/6 twitcher mice under moribund conditions, without any changes in the levels of psychosine, suggesting the involvement of a factor critical for the progression of Krabbe disease other than the accumulation of psychosine in the CNS (74). These observations raise a question as to whether the use of inhibitors of sPLA2, along with anti-inflammatory drugs (e.g., NAC or statins), will protect against the loss of oligodendrocytes and thus increase the life span of twitcher mice or patients with Krabbe disease. At present, there is no treatment for Krabbe disease except hematopoietic stem cell transplantation, which is not a cure, but does slow down the course of the disease in humans as well as in twitcher mice (75–79). Recently, anti-inflammatory therapy with the phosphodiesterase inhibitor ibudilast has been reported to downregulate the inflammation and cell death in twitcher mice (80).

Our findings are summarized in Fig. 9, where we have documented that accumulated levels of psychosine induce the generation of LPC and the release of AA via activation of sPLA2 activity. The initial event may be Ca2+- induced activation of PLA2, with subsequent generation of ROS, and eventually, it may result in a vicious cycle. Using a pharmacological approach, it was confirmed that the psychosine-mediated effects could be nullified by the sPLA2 inhibitor DEDA, which blocks the activation of MAPKs and the generation of ROS by psychosine in oligodendrocyte cells. Antioxidant treatment (NAC) also attenuated LPC accumulation, AA release, ROS generation, and cell death induced by psychosine (4), suggesting the partial involvement of oxidative stress in psychosine-me-
diated effects in oligodendrocytes. Moreover, generation of LPC has been implicated in demyelination (20, 21) by the activation of cell death in mature oligodendrocytes and their progenitors (22, 23). On the other hand, metabolites of AA give rise to oxidative stress, regulating redox-sensitive transcription factors (28–30) and cell death (25, 27). Psychosine-mediated effects are independent of the links to its putative receptor TDAG8 supported by others (45). Altogether, this study documents that psychosine-mediated oligodendrocyte cell death is mediated via the sPLA2 signaling pathway and that inhibitors of sPLA2 may have therapeutic potential for protection against oligodendrocyte cell death and the resulting demyelination in Krabbe disease.

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