The CLN9 Protein, a Regulator of Dihydroceramide Synthase*

Received for publication, August 29, 2005, and in revised form, November 11, 2005 Published, JBC Papers in Press, November 22, 2005, DOI 10.1074/jbc.M509483200

Angela Schulz^{‡§}, Talal Mousallem[‡], Maya Venkataramani[‡], Dixie-Ann Persaud-Sawin[‡], Adam Zucker[‡], Chiara Luberto¹, Alicja Bielawska¹, Jacek Bielawski¹, Joost C. M. Holthuis¹, S. Michal Jazwinski**, Lina Kozhaya^{‡‡}, Ghassan S. Dbaibo^{‡‡}, and Rose-Mary N. Boustany^{‡1}

From the [‡]Duke University Medical Center, Departments of Pediatrics and Neurobiology, Durham, North Carolina 27710, § University Medical Center Hamburg, D-20246 Hamburg, Germany, ¶ Medical University of South Carolina, Department of Biochemistry, Charleston, South Carolina 29425, $^{\parallel}$ Utrecht University, Department of Membrane Enzymology, 3584 CH Utrecht, The Netherlands, **Louisiana State University Health Sciences Center, Department of Biochemistry and Molecular Biology, New Orleans, Louisiana 70112, and ^{‡‡}American University of Beirut Medical Center, Beirut, 1107-2020, Lebanon

A new variant of a group of pediatric neurodegenerative diseases known as neuronal ceroid lipofuscinosis (NCL) or Batten disease has been identified. It is termed CLN9-deficient. CLN9-deficient fibroblasts have a distinctive phenotype of rapid growth and increased apoptosis and diminished levels of ceramide, dihydroceramide, and sphingomyelin. Transfection with CLN8 but not other NCL genes corrected growth and apoptosis in CLN9-deficient cells, although the entire CLN8 sequence was normal. CLN8 is one of the TRAM-Lag1-CLN8 proteins containing a Lag1 motif. The latter imparts (dihydro)ceramide synthase activity to yeast cells. Transfection with the yeast gene Lag1 Sc and the human homolog LASS1 increased ceramide levels and partially corrected growth and apoptosis in CLN9-deficient cells. LASS2, -4, , -5, and -6 also corrected growth and apoptosis. Dihydroceramide levels and dihydroceramide synthase activity were markedly diminished in CLN9-deficient cells. Sequencing of LASS1, LASS2, LASS4, LASS5, and LASS6 genes was normal, and expression levels were increased or normal in CLN9-deficient cells by reverse transcription-PCR. N-(4-Hydroxyphenyl)retinamide (4-HPR), a dihydroceramide synthase activator, corrected growth and apoptosis and increased dihydroceramide synthase activity. Ceramide levels dropped further, and there was no increase in de novo ceramide synthesis, probably due to the effects of 4-HPR as activator of dihydroceramide synthase and inhibitor of dihydroceramide desaturase. Fumonisin B₁, a dihydroceramide synthase inhibitor, exaggerated the CLN9-deficient phenotype of accelerated growth, decreased ceramide and increased apoptosis. This was neutralized by 4-HPR. We conclude that the CLN9 protein may be a regulator of dihydroceramide synthase and that 4-HPR could be developed as a treatment for *CLN9*-deficient patients.

The neuronal ceroid lipofuscinoses (NCL)² are a group of autosomal, recessively inherited storage diseases. They represent the most common cause of neurodegeneration in childhood. Neuronal death is caused by apoptosis (1). Clinical features of these diseases include visual loss, mental and motor deterioration, seizures, and early death (2-3). To date nine forms of NCL have been described. Six genes are known. CLN1 and CLN2 encode for the lysosomal enzymes palmitoyl protein thioesterase 1 and tripeptidylpeptidase 1, respectively (4-5). CLN5p has been described as a soluble glycoprotein (6-7). CLN3, CLN6, and CLN8 genes code for novel transmembrane proteins (8-11). Increased apoptosis has been documented in CLN1-3-, 6-, and -8-deficient vari-

Dysregulated sphingolipid metabolism and increased apoptosis have been described in the late infantile CLN2-, juvenile CLN3-, variant late infantile CLN6-, and the Northern Epilepsy with Mental Retardation CLN8-deficient variants. CLN3 is a negative modulator of ceramide synthesis resulting in high ceramide levels in CLN3deficient patient fibroblasts (14). High ceramide levels, caspase-8 activation, and engagement of both the extrinsic and intrinsic apoptotic pathway as well as caspase-dependent autophagy explain the increased apoptosis and slow growth observed in CLN3-deficient cells. Also, CLN3 protein harbors a galactosylceramide binding motif that is involved in CLN3 trafficking from Golgi to lipid rafts via recycling endosomes (14). The ninth form of NCL, CLN9, has recently been described in four patients; two German brothers and two Serbian sisters (15). These patients present with clinical features identical to those seen in juvenile or CLN3-deficient patients. The CLN9 gene is still unknown. Mutations in all known NCL genes, including CLN3, were ruled out in the CLN9-deficient variant. CLN9-deficient patient fibroblasts have a distinctive phenotype. They have small and rounded cell bodies, grow rapidly, are sensitive to apoptosis and manifest a cell adhesion defect. Their gene expression pattern is significantly different from that in other NCL forms. Genes involved in cell cycle, cell adhesion, and apoptosis are significantly dysregulated (15). Sphingolipid metabolism, similarly to other NCL variants, is also perturbed in CLN9-deficient cells; ceramide, sphingomyelin (SM), lactosylceramide, gangliosides, ceramide trihexoside, and globoside, galactosylceramide, and glucosylceramide are diminished.

The purpose of this study is to dissect out the specific biochemical defect in CLN9-deficient cells, with the ultimate goal of identifying the CLN9 gene and protein. Low levels of lactosylceramide and its metabolites including gangliosides, ceramide trihexoside, and globoside can implicate the seven genes for β -1,4-galactosyltransferase (β 4GalT) and the two for GB3/CD77 synthase as possible candidate genes.

Review of the gene chip data provided additional information; acid sphingomyelinase activity was normal, but mRNA expression of acid sphingomyelinase was 22-fold decreased in the setting of low baseline



^{*} This work was supported by Deutsche Forschungsgemeinschaft Grant SCHU1597/1-1 (to A. S.), by the Serbian Orthodox Church (to R.-M. B.), and also supported by grants from the NIA, National Institutes of Health (to S. M. J.). 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 To whom correspondence should be addressed: Depts. of Pediatrics and Neurobiology, MSRB Box 2604, Durham, NC 27710. Tel.: 919-681-6220; Fax: 919-681-8090; E-mail: boust001@mc.duke.edu.

² The abbreviations used are: NCL, neuronal ceroid lipofuscinosis/dhC16-Cer; 4-HPR, N-(4-hydroxyphenyl)retinamide; Cer, ceramide; SM, sphingomyelin; β 4GalT, β -1,4galactosyltransferase; GB3/CD77, globoside synthase; SMS1 and SMS2, sphingomyelin synthase; TRAM, translocating chain-associated membrane protein; PI, propidium iodide; JC-1, 5,50-60-tetrachloro-1,1,3,3- tetraethylbenzimidazolylcarbocyanine iodide; FB₁, fumonisin B₁; PDMP, phenyl-2-decanoulamino-3-morpholino-1-propranolol; DGK, diacylglycerol kinase; NBD, 12-(N-methyl-N-(7-nitrobenz-2-oxa-1,3diazol-4-yl)).

sphingomyelin levels. Defects in sphingomyelin synthase 1 and/or 2 (SMS1, SMS2) could account for this. A trafficking defect of ceramide from endoplasmic reticulum (ER) to Golgi due to defects in ceramide transporter protein, the ER-to-Golgi ceramide transporter, could also account for low SM (16).

Low ceramide levels also suggest a defect in de novo ceramide synthesis. Activity of serine palmitoyltransferase, the key enzyme of de novo ceramide synthesis, was 4-fold increased, expanding the list of candidate genes to those involved in de novo ceramide synthesis beyond the serine palmitoyltransferase step. Transfection with CLN8 corrected the CLN9 phenotype. The CLN8 protein contains a Lag1 motif similar to other TRAM-Lag1-CLN8 proteins (17). Lag1p and Lac1p are homologous, multispanning transmembrane proteins that reside in the ER. Both contain a 52-amino acid-long Lag1 motif that is necessary for ceramide synthesis in yeast (18-19). Lac1p, Lag1p, and Lip1p are components of the enzyme activity in yeast (20). CLN8 sequencing results were normal in CLN9-deficient cells, suggesting human Lag1 homologs or activators of their proteins could be candidate genes for CLN9.

EXPERIMENTAL PROCEDURES

Cell Lines—CLN9-deficient fibroblast lines were derived from skin biopsies of two CLN9 patients. Use of human cell lines in research is covered by an approved Duke institutional review board protocol.

Tissue Culture Studies-Fibroblasts were grown at 37 °C with 5% CO₂ in Dulbecco's modified Eagle's medium (Invitrogen) containing 10% fetal bovine serum (Invitrogen) and 1% antibiotics/antimycotics.

Growth Curves -1×10^5 cells/well were plated in 6-well plates, then harvested and counted at 24, 48, 72, and 96 h in triplicate for each time point using the trypan blue dye exclusion method.

Trypan Blue Dye Exclusion—Harvested cells were centrifuged at 1200 rpm for 5 min, and pellets were suspended in a 1:1 mixture of 4% trypan blue dye (Invitrogen) and 1× phosphate-buffered saline and loaded onto a hemocytometer. Viable white and dead blue cells were counted.

Etoposide Treatment—Cells were treated with 10 µg/ml etoposide (Sigma) for 18 h. Apoptosis was determined by propidium iodide (PI), JC-1, or terminal dUTP nick-end labeling staining.

4-HPR Treatment—Cells were treated with 2.5, 5, and 10 μ M 4-HPR (Sciencelab.com, Houston, TX). 4-HPR was dissolved in ethanol at a concentration of 10 mM and stored at −20 °C. Stock solutions were diluted to the required concentrations with growth medium just before

Fumonisin B₁ Treatment—Cells were treated with 1 μM fumonisin B₁ (FB₁) (Sigma). FB₁ was dissolved in Me₂SO at a concentration of 1 mm and stored at -20° C. Stock solutions were diluted to the required concentration with growth medium just before use.

PDMP Treatment—Cells were treated with 20 μM PDMP (Sigma). PDMP was dissolved in Me₂SO at a concentration of 20 mm and stored at −20°C. Stock solutions were diluted to the required concentration with growth medium just before use.

Transfection—Cells were transfected with different cDNA-vector constructs: CLN1-pGEM, CLN2-pGEM, CLN3-pGEM, CLN6pGEM, CLN8-pGEM (cDNAs amplified and cloned as previously described), Lag1-pGEM, LASS1-pIRES2-EGFP (cDNA clones provided by S. M. Jazwinski), LASS1trv3-pGEM, LASS2trv1/2-pGEM, LASS3-pIRES2-EGFP, LASS5-pGEM (cDNA clones purchased from Open Biosystems, Huntsville, AL), LASS2trv3-pGEM (cDNA clone purchased from OriGene Technologies Inc, Rockville, MD), LASS4pBluescript (cDNA clone purchased from RZPD, Berlin, Germany). The protocols for the Lipofectamine 2000 Transfection kit (Invitrogen) were followed. The cells were washed and plated for analysis. Transfection efficiency of pGEM-transfected cells was determined using an YFP-pGEM construct and counting yellow fluorescent cells/total cells/vision field in triplicate under fluorescent microscopy. Transfection efficiency of pIRES2-EGFP-transfected cells was determined by counting green fluorescent cells/total cells/vision field in triplicate under fluorescent microscopy. Transfection efficiency of pcDNA3.1/V5-His-TOPO-transfected cells was determined using a pcDNA3.1/V5-His-TOPO-LacZ construct. Transfected cells were stained using a β -galactosidase staining kit (Invitrogen). Transfection efficiency was determined counting stained cells/total cells/vision field in triplicate under light microscopy.

Sequencing—All exons including exon-intron junctions of GB3/ CD77 synthase, \(\beta 4Galt1-7\), LASS1, LASS2, and LASS4, were amplified from genomic DNA of CLN9-deficient cells. Entire coding regions of LASS5, LASS6, SMS1, and SMS2 were amplified from cDNA of CLN9deficient cells. Products were sequenced using an automated sequencer (377XL Prism DNA Sequencer; PE Biosystems, Foster City, CA).

PI Staining—Equal numbers of cells treated/not treated with etoposide were grown on coverslips and stained with PI (5 μ g/ml) for 5 min. Three fields of vision were chosen randomly at 100× magnification. The total number of cells/field of vision (20 – 60 cells/field) was counted. The number of PI-positive red apoptotic cells was determined under fluorescence (excitation wavelength, 525 nm; emission wavelength, 600 nm). The percentage of PI-positive cells/total cells/field of vision was calculated. Average and S.D. were determined, and statistical significance was calculated using Student's t test.

JC-1 Staining—JC-1 stain (5,50-60-tetrachloro-1,1,3,3-tetraethylbenzimidazolylcarbocyanine iodide; Molecular Probes, Eugene, OR) was used to assess the decrease in mitochondrial membrane potential after treatment with etoposide. JC-1 is a cationic dye that forms J-aggregates with the cytochrome c-apoptosis protein-activating factor-1 complex. Cells undergoing apoptosis are visualized when a shift in the emission spectrum from green (525 nm) to red (590 nm) occurs. This shift signals the onset of apoptosis. Equal numbers of cells treated/not treated with etoposide were grown on coverslips. The cells were then washed with $1 \times phosphate-buffered$ saline and incubated with 1 mg/ml of JC-1 stain for 15 min at 37 °C and in 5% CO₂. The cells were again washed in phosphate-buffered saline and the mounted on a slide with 1:1 phosphate-buffered saline: glycerol mix. Red apoptotic and total cells in three different fields of vision were counted (100-200 cells/field). The percentage of red apoptotic cells/total cells/field of vision was calculated as well as average and S.D. Statistical significance was determined using Student's t test.

Analysis of Exogenous Ceramide Trafficking-Equal numbers (1 × 10⁵) of normal and *CLN9*-deficient fibroblasts were grown on coverslips and incubated in a solution containing Hanks' balanced salt solution, 10 mm HEPES (Invitrogen), 1% (w/v) fatty acid free bovine serum albumin (Sigma), and 5 μ m C6-NBD-ceramide at 16 °C for 3 h. Cells were then washed in HEPES-buffered saline solution followed by back exchange for 30 min in HEPES-buffered saline solution-bovine serum albumin. Cells were mounted onto a glass slide with 1 drop of Fluoromount (Southern Biotechnology Associates, Birmingham, AL) and viewed with a Leica DMLB fluorescent microscope.

Ceramide and Dihydroceramide Levels—Ceramide and dihydroceramide levels were quantified by mass spectrometry (Lipidomics Core,



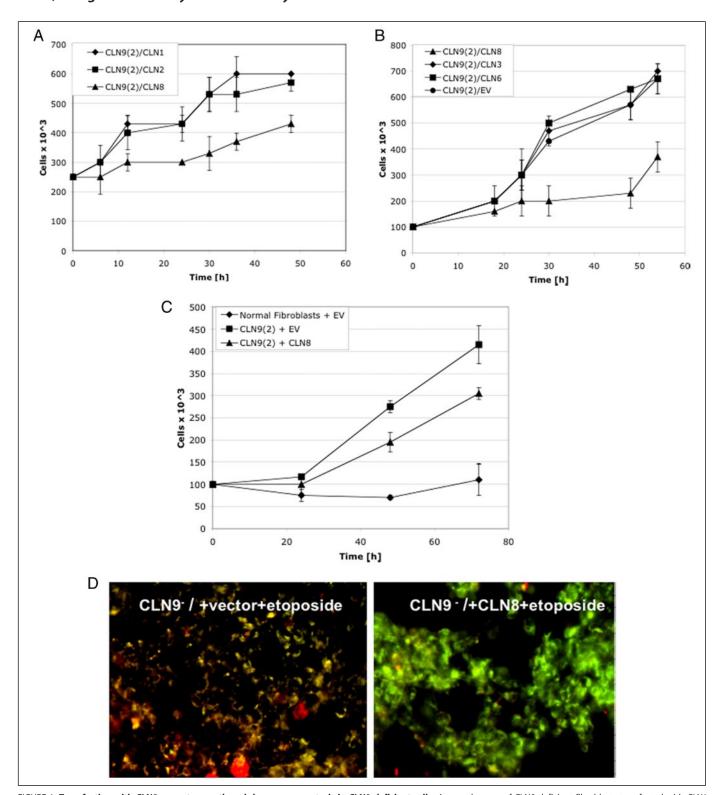


FIGURE 1. Transfection with CLN8 corrects growth and decreases apoptosis in CLN9-deficient cells. A, growth curve of CLN9-deficient fibroblasts transfected with CLN1 (diamonds), CLN2 (squares), and CLN8 (triangles). Live cells were counted in triplicate at different timepoints. B, growth curve of CLN9-deficient fibroblasts transfected with CLN3 (diamonds), CLN6 (squares), empty vector (EV, circles) and CLN8 (triangles). Live cells were counted in triplicate at different time points. A significant decrease in growth rate is seen in cells transfected with CLN8. C, growth curve of CLN9-deficient fibroblasts transfected with empty vector (squares) or CLN8 (triangles) and normal fibroblasts transfected with empty vector (diamonds). A significant decrease in growth rate is seen in cells transfected with CLN8. The growth rate of empty vector-transfected normal fibroblasts is even lower. D, JC-1-staining of CLN9-deficient fibroblasts transfected with empty vector or CLN8 after etoposide treatment. Apoptotic cells are red, and healthy cells are green. CLN8 decreases apoptosis (number of green healthy cells).

Medical University of South Carolina) according to published methods. Ceramide and dihydroceramide levels were also measured by DGK assay using diacylglycerol kinase from Escherichia coli (Sigma) and 1.3

μCi of ATP/sample (Amersham Biosciences) using standards for C16, C24, and C24:1 ceramides and the corresponding dihydroceramides (Avanti, Alabaster, AL).

Dihydroceramide Synthase Activity—Dihydroceramide synthase activity was determined by measuring de novo dihydroceramide generated per hour after labeling cells with C17-dihydrosphingosine (C6dihydrosphingosine with C17 backbone) (molecular mass, 287.5 g/mol; $5 \mu m$) for 4 h.

Sphingomyelin Synthase Activity—Cells were washed three times with phosphate-buffered saline, harvested using a rubber policeman, and homogenized in 1 ml of 25 mM KCl and 25 mM Tris-Cl (pH 7.4) (TK buffer) and 0.5 mm EDTA. Cells were homogenized by 20 passages through a 27-gauge needle. Homogenates were used fresh. SM synthesis was assayed as described. The reaction mixture contained 100 µg of protein, 10 μ l of NBD-6-ceramide (1 mM), and 1.7 μ l of phosphatidylcholine (10 mg/ml) in a total volume of 300 μ l of TK buffer. The reaction was terminated after 90 min at 37 °C by the addition of 1 ml of chloroform, 1 ml of methanol, and 400 μ l of water. Lipids were then extracted according to Bligh and Dyer, and SM spots were separated on TLC using chloroform/methanol/CaCl₂ (15 mM) solution (120:70:16 v/v/v) as the developing solvent. TLC plates were analyzed using a PhosphorImager, and bands were quantified by ImageQuant software (Amersham Biosciences Version 2003).

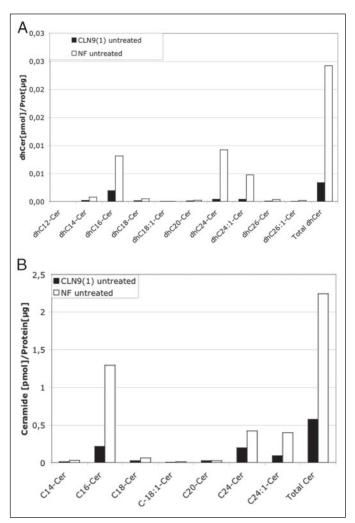
Real-time PCR—Total RNA was isolated from normal and CLN9deficient fibroblasts using the Qiagen RNeasy mini kit (Qiagen, Valencia, CA). Reverse transcription reactions were carried out with Super Script III first-strand synthesis system (Invitrogen). Real-time PCR was performed using total cDNA and Absolute QPCR SYBR Green Fluorescence Mix (Abgene Inc., Rochester, NY) according to the manufacturer's protocol in a Bio-Rad I-Cycler. The mRNA levels of cyclophilin/ hypoxanthine-guanine phosphoribosyltransferase/28 S ribosomal RNA were used as internal controls.

RESULTS

CLN8 Corrects Growth and Apoptosis in CLN9-deficient Cells—CLN9deficient fibroblasts were transfected with CLN1, CLN2, CLN3, CLN6, and CLN8 genes individually and were assessed for growth and sensitivity to apoptosis. Only transfection with CLN8, out of all NCL genes, partially corrected growth in CLN9-deficient cells (Fig. 1, A and B). CLN9-deficient cells transfected with CLN8 cDNA showed a significant decrease in growth rate compared with CLN9deficient cells transfected with empty vector. Growth rate still exceeded that of normal fibroblasts transfected with empty vector (EV) (Fig. 1C). Transfection with CLN8 decreased sensitivity to apoptosis in CLN9-deficient fibroblasts. Cells transfected with CLN8 or empty vector were stained with JC-1 after 16 h of etoposide treatment. Cells transfected with CLN8 showed significantly less red J-aggregate formation than controls transfected with empty vector (Fig. 1D).

Dihydroceramide Synthase Activity; Dihydroceramide and Ceramide Levels Are Low in CLN9-deficient Cells—CLN9-deficient cells have significantly decreased dihydroceramide synthase activity, as reflected by the decreased levels of dihydroceramide and ceramide in CLN9-deficient cells. The most significant decreases were in dhC16-, dhC24-, and dhC26-ceramide and C16-, C24-, and C24:1-ceramide species compared with control cells (Fig. 2, A and B). DhC24-Cer, dhC24:1-Cer, and dhC26:1-Cer levels were 4.4, 8.2, and 9.5%, respectively, compared with normal controls. Dihydroceramide synthase activity was measured by labeling cells with C17 dihydrosphingosine and measuring dihydroceramide generated over 4 h (see Fig. 5G).

Lag1 Sc Increases Ceramide and Corrects Growth and Apoptosis in CLN9-deficient Cells-Transfection with Lag1 Sc increased total ceramide levels in CLN9-deficient cells 105% above levels in cells trans-



 ${\sf FIGURE~2.} \ \textbf{Low dihydroceramide and ceramide levels in CLN9-deficient cells.} \ \textit{A}, \\ \textit{dihydroceramide and ceramide levels in CLN9-deficient cells.} \ \textit{A}, \\ \textit{dihydroceramide and ceramide levels in CLN9-deficient cells.} \ \textit{A}, \\ \textit{dihydroceramide and ceramide levels in CLN9-deficient cells.} \ \textit{A}, \\ \textit{dihydroceramide and ceramide levels in CLN9-deficient cells.} \ \textit{A}, \\ \textit{dihydroceramide and ceramide levels in CLN9-deficient cells.} \ \textit{A}, \\ \textit{dihydroceramide and ceramide levels in CLN9-deficient cells.} \ \textit{A}, \\ \textit{dihydroceramide and ceramide levels in CLN9-deficient cells.} \ \textit{A}, \\ \textit{dihydroceramide and ceramide levels in CLN9-deficient cells.} \ \textit{A}, \\ \textit{dihydroceramide and ceramide levels in CLN9-deficient cells.} \ \textit{A}, \\ \textit{dihydroceramide and ceramide levels in CLN9-deficient cells.} \ \textit{A}, \\ \textit{dihydroceramide and ceramide levels in CLN9-deficient cells.} \ \textit{A}, \\ \textit{dihydroceramide and ceramide levels in CLN9-deficient cells.} \ \textit{A}, \\ \textit{dihydroceramide and ceramide and ceramide and ceramide levels in CLN9-deficient cells.} \ \textit{A}, \\ \textit{dihydroceramide and ceramide and ceramide and ceramide and ceramide and cells.} \ \textit{A}, \\ \textit{dihydroceramide and cells.}$ droceramide species levels are significantly decreased in CLN9-deficient cells compared with normal fibroblasts (NF). Dihydroceramide levels were measured by tandem mass spectrometry (values from single measures are shown). B, ceramide species levels in CLN9-deficient cells are significantly decreased in CLN9-deficient cells compared with normal fibroblasts. Ceramide levels were measured by tandem mass spectrometry (values from single measures are shown).

fected with empty vector. This was determined by DGK assay (Fig. 3A). Tandem mass spectrometry showed an increase in the long chain ceramide species C18-Cer/C20-Cer/C24:1-Cer/C24-Cer (data not shown).

Lag1 Sc decreased growth rate after transfection (Fig. 3B). Lag1 Sc also decreased sensitivity to apoptosis by PI staining after treatment with etoposide. Two CLN9-deficient cell lines had a 32.4 and 29.6% apoptotic rate after transfection with empty vector compared with a 12.8 and 4.1% apoptotic rate after transfection with Lag1 Sc (Fig. 3C). Normal fibroblasts, on the other hand, had increased apoptosis after transfection with Lag 1 Sc (22.6 versus 40.6%, Fig. 3C). Baseline ceramide levels were higher in normal fibroblasts (Fig. 2B). Lag1 Sc overexpression leads to higher, proapoptotic ceramide levels. In conclusion, yeast Lag1 Sc partially corrected ceramide levels, growth, and apoptosis in CLN9-deficient cells.

Human Lag1 Homologs Correct Ceramide, Growth, and Apoptosis in CLN9-deficient Cells—LASS1 is the human homolog to Lag1 Sc. LASS1 increased total ceramide levels more than 4-fold in CLN9-deficient cells, as determined by DGK assay (Fig. 4A). [14C]Palmitate labeling established an increase in de novo ceramide synthesis as well (data not



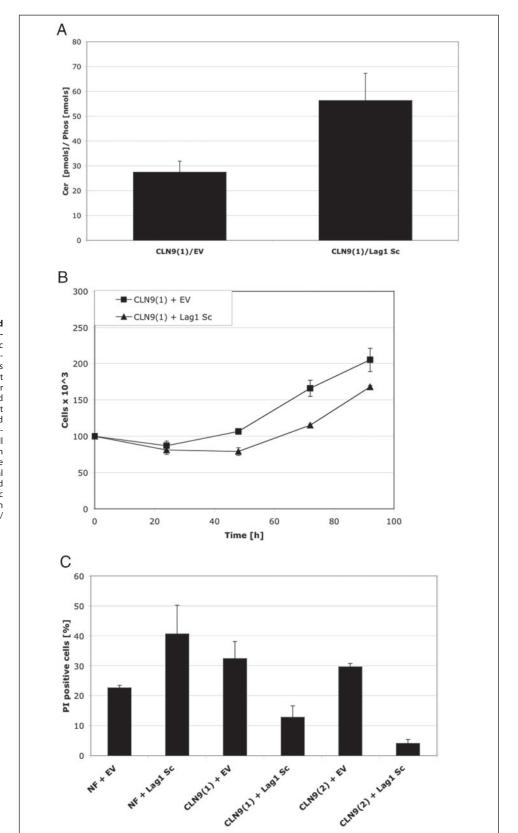


FIGURE 3. Lag1 Sc corrects ceramide levels and growth rate and decreases apoptosis in CLN9deficient cells. A, transfection with Lag1 Sc increases ceramide levels compared with transfection with empty vector (EV) in CLN9-deficient cells (DGK assay). B, growth curve of CLN9-deficient fibroblasts transfected with Lag1 Sc (triangles) or empty vector (EV, squares). Live cells were counted in triplicates at different time points. A significant decrease in growth rate is seen in cells transfected with Lag1 Sc. C, propidium iodide staining of normal (NF) and two CLN9-deficient fibroblast cell lines (CLN9 (1) and CLN9 (2)) after treatment with etoposide. Transfection with Lag1 Sc increases the number of PI positive apoptotic cells in normal fibroblasts (22.6 versus 40.6%, p value 0.04) and decreases the number of PI-positive apoptotic cells in CLN9-deficient fibroblasts compared with empty vector transfection (32.4/29.6 versus 12.8/ 4.1%, p values 0.006/0.001).

shown). LASS1 increased mass measurements of C18- and C18:1-ceramide species by 100% in normal fibroblasts and 300% in CLN9-deficient fibroblasts after transfection (Fig. 4B). This is consistent with published reports on LASS1 ceramide species specificity.

LASS1 partially corrected growth rate in CLN9-deficient cells (Fig. 4C), and decreased cell proliferation as shown by [H3]thymidine incorporation (data not shown). LASS1 decreased CLN9-deficient cell sensitivity to apoptosis as observed by PI staining (Fig. 4D) and JC-1 staining

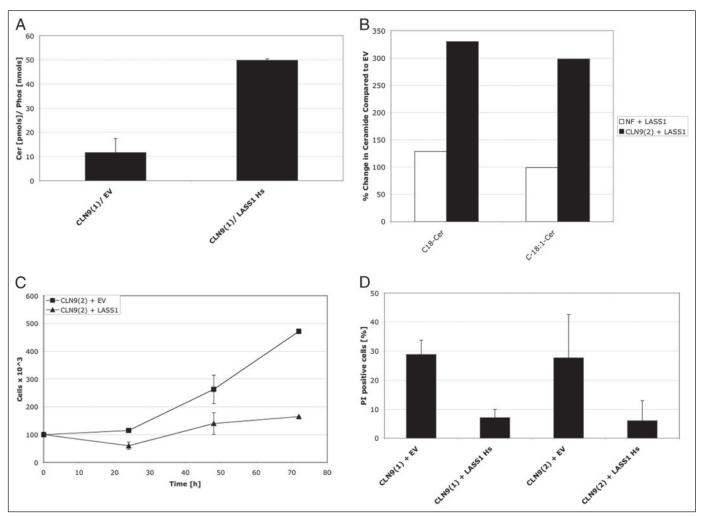


FIGURE 4. LASS1 corrects ceramide levels, growth rate, and decreases apoptosis in CLN9-deficient cells. A, transfection of CLN9-deficient cells with LASS1 increases ceramide levels compared with transfection with empty vector (EV) (DGK assay). B, transfection with LASS1 increases levels of C18-Cer and C18:1-Cer species in both normal (NF) and CLN9-deficient fibroblasts (values from single measures by tandem mass spectrometry are shown). C, CLN9-deficient fibroblasts transfected with LASS1 (triangles) or empty vector (squares). Live cells were counted in triplicates at different time points. A significant decrease in growth rate is seen in cells transfected with LASS1. D, propidium iodide staining of two CLN9-deficient fibroblast cell lines (CLN9 (1) and CLN9 (2)) after treatment with etoposide. Transfection with LASS1 decreases the number of PI-positive apoptotic cells in CLN9deficient fibroblasts compared with empty vector transfection.

(data not shown). LASS1 sequences were normal in CLN9-deficient cells. Other human Lag1 homologs LASS1-LASS6 (including multiple transcript variants) were tested for their ability to correct the CLN9 phenotype. All except LASS3 partially corrected growth and diminished apoptosis in CLN9-deficient cells (data not shown). LASS1, LASS2, LASS4, LASS5, and LASS6 sequences were normal in CLN9-deficient cells. LASS2 expression levels were normal, and LASS1, -3, -4, and -6 expression levels were increased 12.7-, 6.2-, 9.6-, and 4.3-fold excluding the possibility that the CLN9 gene could be one of the known human Lag1 homologs.

4-HPR Increases Dihydroceramide Synthase Activity and Dihydroceramide Levels, Corrects Growth, and Decreases LASS1 Expression by Reverse Transcription-PCR-CLN9-deficient cells were treated with fenretinide or 4-HPR, a dihydroceramide synthase activator (21). Treatment with 4-HPR increased dihydroceramide levels in both normal and CLN9-deficient fibroblasts. Normal fibroblasts showed an increase of all dihydroceramide species except dhC18:1-Cer. CLN9-deficient cells showed an increase in all dihydroceramide species that was significantly higher than the increase in normal cells. dhC16-Cer, dhC24-Cer, and dhC26:1-Cer levels increased the most after 4-HPR treatment and were elevated 244-, 359-, and 320-fold, respectively, in CLN9-deficient cells

(Fig. 5 A). The same dihydroceramide species had the lowest levels in untreated CLN9-deficient cells (Fig. 2A).

Dihydroceramide synthase activity was also increased by 4-HPR (Fig. 5G). There was, however, no increase in rate of de novo ceramide synthesis after 4-HPR treatment in CLN9-deficient cells as measured by [14C]palmitate labeling. Treatment with 4-HPR decreased levels of all ceramide species as measured by tandem mass spectrometry (Fig. 5B). This effect might be due to a combined action of 4-HPR as activator of dihydroceramide synthase and inhibitor of dihydroceramide desaturase.3

Treatment with 4-HPR corrected growth of CLN9-deficient cells in a time- and dose-dependent manner. Continuous treatment with 4-HPR at the same concentration showed significant decrease of growth in CLN9-deficient cells after 48 h (Fig. 5C). Treatment with 2.5 μ M 4-HPR did not have a significant effect on growth, but 5 and 10 μ M 4-HPR decreased growth in a dose-dependent manner (Fig. 5C). There was no effect of 4-HPR on growth of normal cells when used at the same concentration (data not shown). 4-HPR decreased LASS1 expression to



³ A. Merrill, personal communication.

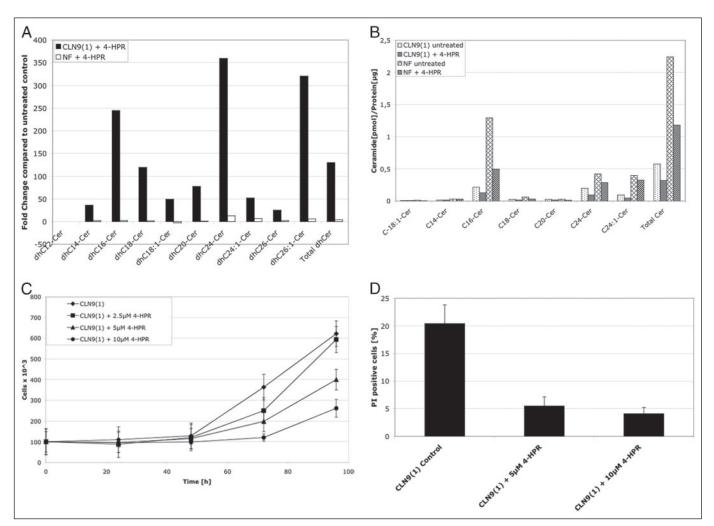


FIGURE 5. 4-HPR activates dihydroceramide synthase, corrects dihydroceramide levels, growth, and decreases apoptosis in CLN9-deficient cells. A, treatment with 4-HPR increases dihydroceramide species levels more significantly in CLN9-deficient cells than in normal fibroblasts (NF) as measured by tandem mass spectrometry. -Fold changes compared with untreated control are shown (values are from single measures). B, treatment with 4-HPR decreases ceramide species levels in CLN9-deficient and normal fibroblasts as measured by tandem mass spectrometry (values from single measures). C, growth curve of CLN9-deficient fibroblasts untreated (diamonds), treated with 2.5 μ M 4-HPR (squares), 5 μμ 4-HPR (triangles), and 10 μμ 4-HPR (circles). Live cells were counted in triplicates at different time points. A significant dose-dependent decrease in growth rate is seen in cells treated with 4-HPR. D—E, propidium iodide staining of CLN9-deficient fibroblasts after treatment with 4-HPR and/or PDMP. Treatment with 4-HPR decreases the number of Pl-positive apoptotic cells in a dose-dependent manner (20.4 untreated versus 5.4/4.1% treated with 5 and 10 μ m 4-HPR, p value 0.009). Treatment with PDMP decreases the number of PI-positive apoptotic cells. Treatment with both 4-HPR and PDMP increases the number of PI-positive apoptotic cells. F, DGK assay measuring ceramide and dihydroceramide in CLN9-deficient cells treated with 4-HPR alone, PDMP alone, or both. Note that the combined total of ceramide and dihydroceramide is very low in untreated cells, somewhat higher in 4-HPR (~2-fold)- and PDMP (~1.5-fold)-treated cells, but much higher in 4 HPR + PDMP-treated cells (~5-fold). G, dihydroceramide synthase activity; shown is de novo C17 dihydroceramide generation 4 h before and after treatment with 4-HPR (values from single measures by tandem mass spectrometry). Treatment with 4-HPR increases de novo dihydroceramide generation (reflecting increased dihydroceramide synthase activity).

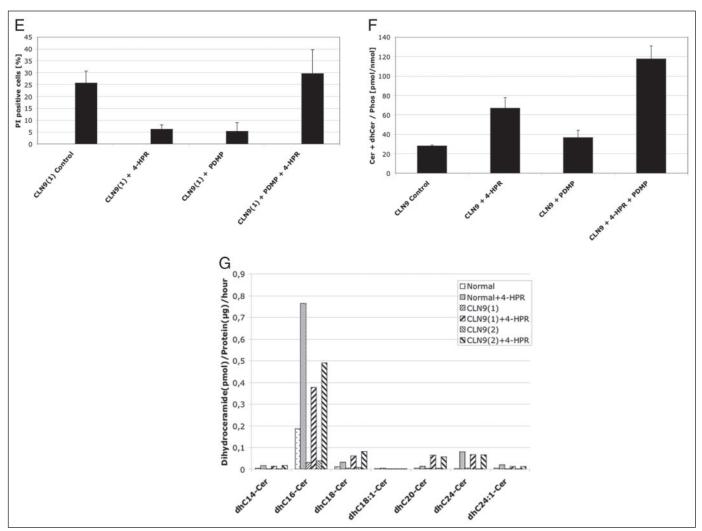
0.22-fold in mRNA from untreated CLN9-deficient cells. In normal cells 4-HPR decreased LASS1 expression to 0.5-fold expression from normal fibroblasts.

4-HPR or PDMP Protects CLN9-deficient Cells from Apoptosis—Treatment with 4-HPR protected CLN9-deficient cells from apoptosis. Cells treated with 4-HPR showed significantly less apoptosis by PI staining (20.4% untreated versus 5.4% treated with 5 μ M 4-HPR). This effect was dose-dependent. 10 μ M 4-HPR decreased apoptosis even further (4.1%; Fig. 5D). These results were confirmed by JC-1 and terminal dUTP nick-end labeling staining.

4-HPR normally increases apoptosis (22). CLN9-deficient cells were protected from apoptosis by 4-HPR. Treating CLN9-deficient cells with PDMP, which inhibits glucosylceramide synthase, results in an increase in ceramide mass measurements (23). PDMP diminished apoptosis in CLN9-deficient cells. Treatment with PDMP and 4-HPR, however, increased apoptosis above the level of untreated CLN9-deficient cells. This was determined by PI staining (Fig. 5*E*). This effect may be due to

the combined effect of an increase in ceramide due to PDMP and an increase in dihydroceramide due to 4-HPR (Fig. 5F). These drugs act at different steps of the pathway.

Fumonisin B,, a Dihydroceramide Synthase Inhibitor, Exaggerates the CLN9 Phenotype—To confirm that the CLN9-phenotype could be due to a defect in activation of dihydroceramide synthase, FB₁ was used. It inhibits dihydroceramide synthase and should, therefore, exaggerate the CLN9 phenotype. Pretreatment with FB₁ decreased base-line low ceramide levels in CLN9-deficient cells even further. 4-HPR neutralized the effect of FB₁ on ceramide levels. Ceramide levels were measured by DGK assay after 34 h of 4-HPR treatment (Fig. 6A). FB₁ treatment accelerated growth of CLN9-deficient cells, exaggerating the CLN9 phenotype. Treatment with 4-HPR opposed this increase in growth (Fig. 6B). CLN9-deficient cells pretreated with FB₁ also had a higher apoptotic rate than untreated cells. FB₁ opposed the protective effect of 4-HPR. The effects on apoptosis were amplified in the presence of etoposide as visualized by PI staining and confirmed by JC-1 staining (Fig. 6C).



Low Sphingomyelin in CLN9-deficient Cells Is Not Due to a Ceramide Trafficking Defect—Ceramide produced at the ER is transported via ceramide transporter protein or ceramide transporter protein to the lumen of the Golgi for conversion to SM by sphingomyelin synthase 1 (16). Should a ceramide trafficking defect be present, sphingomyelin synthase activity would be elevated. Sphingomyelin synthase activity was 40% of normal, negating the possibility of a ceramide trafficking defect in CLN9-deficient cells. Also, CLN9-deficient cells, when exposed to fluorescent NBD-C6-ceramide, demonstrated an intensely fluorescent Golgi reflecting normal trafficking and uptake of ceramide with conversion to SM in the Golgi lumen (Fig. 7).

The CLN9 phenotype is best explained by the extremely low dihydroceramide and ceramide levels. Increasing dihydroceramide by 4-HPR or ceramide by PDMP corrected the phenotype.

DISCUSSION

CLN9-deficient cells manifest increased apoptosis but accelerated growth combined with very low ceramide levels (15). The marked decrease in de novo lactosylceramide synthesis and glycosphingolipids and gangliosides derived from it begged the question of whether one of the seven β -1,4-galactosyltransferases (β 4GalT1-7) or GB3/CD77 synthase could be candidates for CLN9. All seven \(\beta 4 \text{GalT}\) proteins are membrane proteins that reside in the Golgi, and the latter is also the seat of SM synthesis from ceramide and lactosylceramide synthesis from

glucosylceramide (24-25). A defect in \(\beta 4 \text{GalT7}\) had already been described in a patient with a progeroid, Ehlers-Danlos-like syndrome (26). We ruled out mutations in these genes in CLN9 patients by sequence analysis. Low sphingomyelin suggested a possible defect in sphingomyelin synthesis. SM synthase proteins SMS1 and SMS2 reside in the Golgi and the plasma membrane, respectively (27-28). Sphingomyelin synthase activities were 40% of normal, and sequences of both of SMS1 and SMS2 were intact in CLN9-deficient cells. Also, SMS1 and SMS2 gene expression in CLN9-deficient cells was comparable with normal. Moreover, overexpression of SMS1 or SMS2 in CLN9-deficient cells had no effect on growth, essentially ruling them out as candidate

Transfection with CLN8 corrected growth and decreased apoptosis in CLN9-deficient cells. Human dihydroceramide synthase is still poorly characterized. Overexpression of the yeast gene Lag1 Sc and LASS1, the human Lag1 homolog for Lag1 Sc, complemented the defect in CLN9 cells with correction of ceramide levels, growth, and apoptosis.

The inhibiting effect of ceramide on cell growth is well known. The mouse homologue of Lag1 increases C18-ceramide and decreases cell growth in head and neck squamous cell carcinoma cells derived from head and neck tumors (29). LASS1 Hs is primarily expressed in brain, with very low levels of expression in skeletal muscle and testis. Genes involved in neurodegenerative diseases have a distribution pattern similar to that of human LASS1 or LASS1 Hs (30). Analysis of tissue distri-

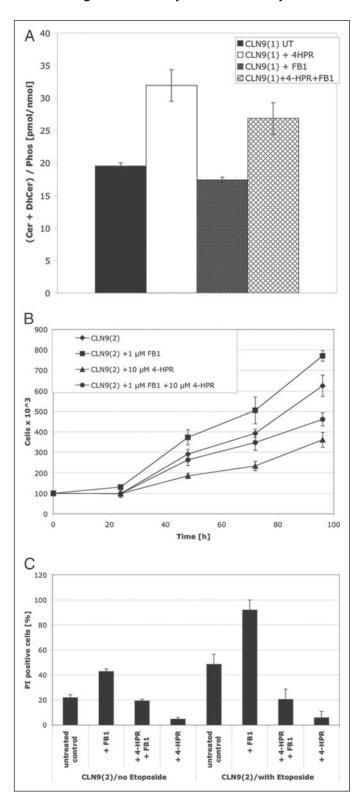


FIGURE 6. Opposing effects of 4-HPR and FB₁ on ceramide levels, growth, and apoptosis. A, treatment with FB1 decreases ceramide and dihydroceramide levels in CLN9deficient cells measured at 34 h by DGK assay. Treatment with 4-HPR neutralizes the effect of FB₁ on ceramide and dihydroceramide levels. UT, untreated. B, growth curve of CLN9-deficient fibroblasts untreated (diamonds), pretreated with FB₁ (squares), treated with 4-HPR (triangles), and treated with both FB₁ and 4-HPR (circles). Live cells were counted in triplicate at different time points. FB₁ treatment increases the growth rate, exaggerating the CLN9-deficient phenotype. Treatment with 4-HPR neutralizes the increase in growth after FB₁. C, propidium iodide staining of CLN9-deficient fibroblasts treated with FB₁ and/or 4-HPR. Treatment with FB₁ increases apoptosis in CLN9-deficient cells even more and opposes the protective effect of 4-HPR on apoptosis. This is shown in cells without and with etoposide treatment.

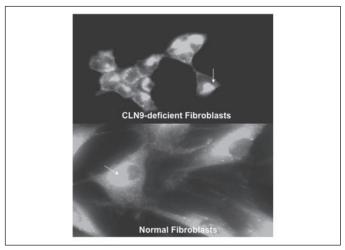


FIGURE 7. Ceramide traffics correctly from the ER to the Golgi lumen in normal and CLN9-deficient cells. Treatment of normal (lower panel) and CLN9-deficient fibroblasts (upper panel) with fluorescently labeled NBD C-6 ceramide at 16 °C for 3 h resulted in uptake of ceramide by the Golgi with conversion to sphingomyelin within the Golgi lumen by sphingomyelin synthase 1. The white arrows point to eccentric intensely fluorescent Golgi next to an oval-shaped dark nucleus. Note much smaller CLN9-deficient cells (magnification \times 100).

bution of mouse LASS1, LASS2, LASS4, LASS5, and LASS6 confirmed that only LASS1 expression was mostly brain-specific (31). A normal LASS1 sequence as well as elevated levels of gene expression in CLN9deficient cells excludes LASS1 from being a candidate for CLN9. All other human Lag1 homologs except LASS3 could partially correct growth and apoptosis in CLN9-deficient cells. LASS3 contains both a Lag1 motif and a Hox domain. Studies in yeast cells led to the hypothesis that both motifs are important for ceramide synthesis (32). Our results indicate that in mammalian cells this is not necessarily true. Transfection with either LASS1, LASS2 transcript variant 1 or 2, or LASS2 transscript variant 3 corrected growth and apoptosis in *CLN9*-deficient cells. LASS2 transcript variants 1 and 2 contain both a Lag1 motif and a Hox domain. LASS2 transcript variant 3 lacks the Hox domain but was still able to complement CLN9. Only the Lag1 motif and not the Hox domain is sufficient and necessary for ceramide synthesis in human fibroblasts. Low dihydroceramide levels and low de novo dihydroceramide synthesis and increases in LASS1, LASS3, LASS4, and LASS6 expression by reverse transcription-PCR suggest that CLN9 may be a modulator of dihydroceramide synthase at the protein level. 4-HPR, an activator of dihydroceramide synthase, increased dihydroceramide levels in CLN9-deficient cells. Dihydroceramide levels were markedly increased in both CLN9-deficient and normal fibroblasts by the drug. 4-HPR increased de novo dihydroceramide synthesis but did not increase de novo synthesis or mass levels of ceramide. This was not surprising as 4-HPR also inhibits dihydroceramide desaturase.³

Increases in dihydroceramide levels in CLN9-deficient cells corrected growth and decreased apoptosis. Dihydroceramide has been found to be biologically inactive in some cell systems (33). The data from CLN9deficient cells presented here suggest that dihydroceramide may be biologically active when ceramide levels are extremely low, resulting in modulation of growth and apoptosis.

4-HPR is used as a ceramide-modulating chemotherapeutic agent. A dose- and time-dependent increase in ceramide after 4-HPR treatment has been described in neuroblastoma cell lines, prostate and breast cancer cells, lymphoblastic leukemia cells, and Ewing family tumors as well (34-38). Maurer et al. (39) showed that 4-HPR did not increase ceramide in non-malignant fibroblasts and Epstein-Barr virus-transformed lymphoblastoid cell lines. Our data also suggest that 4-HPR has different



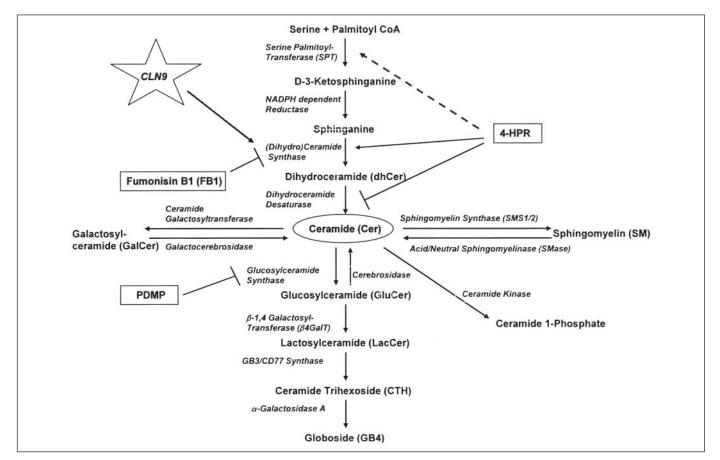


FIGURE 8. Schematic of the sphingolipid synthetic pathway. The sites of action of the various sphingolipid activators and inhibitors used in this study and the location of the hypothesized CLN9 action are indicated. The arrows represent activating action, and the lines represent inhibiting action.

biologic effects depending on base-line ceramide and dihydroceramide levels of the specific cell type; there is protection from apoptosis in CLN9-deficient cells and an increase in apoptosis in normal fibroblasts. We hypothesize that base-line dihydroceramide and ceramide levels in cells determine the effect of 4-HPR on apoptosis. Dihydroceramide levels in CLN9-deficient cells are increased by treatment with 4-HPR, but ceramide levels are lowered even further. PDMP increases ceramide but not dihydroceramide levels. Each of the treatments alone results in protection from apoptosis. Treatment with both 4-HPR and PDMP increased apoptosis in CLN9-deficient cells. This is most likely due to a simultaneous increase of dihydroceramide and ceramide levels. 4-HPR can cause both apoptosis and p53- and caspase-independent cell loss without increases in ceramide (22). Lovat et al. (13) describe that inhibitors of acid sphingomyelinase, but not dihydroceramide synthase, block 4-HPR-induced apoptosis in neuroblastoma cells. Treatment with both 4-HPR and desipramine, an inhibitor of acid sphingomyelinase, did not change the protective effect of 4-HPR on apoptosis in CLN9-deficient fibroblasts (data not shown). There are two paradoxes here; 4-HPR protects CLN9-deficient cells from apoptosis, and this occurs in the setting of an increase in dihydroceramide and a further decrease in ceramide levels. PDMP, which increases ceramide levels but has no effect on dihydroceramide levels, also protects these cells from apoptosis. This can be explained in multiple ways; 1) a threshold lower level of ceramide is necessary for the well-being of cells, below which apoptosis is activated, 2) when ceramide levels are very low, dihydroceramide assumes some of the biologic functions of ceramide, and the sum total of ceramide and dihydroceramide determines biologic function, or

3) variations in levels of another biologically active sphingolipid metabolite(s) can explain these findings.

The findings of low dihydroceramide levels and partial correction of the CLN9-deficient phenotype by human LAG1 homologs, except LASS3, suggested that CLN9 could be a human Lag1 homolog or a regulator of dihydroceramide synthase (Fig. 8). Normal Lag1 homolog sequences, elevated levels of expression of human LASS genes by reverse transcription-PCR, increases in dihydroceramide levels, and a drop in LASS1 expression in response to 4-HPR, however, indicate that CLN9 could be an activator of dihydroceramide synthase should the mutation in CLN9 result in loss of function. Likewise, a gain of mutation function such as in a duplication of a gene or a CLN9 mutation resulting in tighter binding of the inhibitor to dihydroceramide synthase may suggest that CLN9 or mutated CLN9 could be an inhibitor of dihydroceramide synthase activity at the protein level. This work also has diagnostic and therapeutic implications; determination of dihydroceramide levels by tandem mass spectrometry can be developed as a diagnostic test for ascertainment of new CLN9-deficient cases. Moreover, the oral drug 4-HPR, a dihydroceramide synthase activator, may also have potential as a treatment option for CLN9-deficient patients.

Acknowledgment—We thank the affected families for participating in this study.

REFERENCES

1. Lane, S. C., Jolly, R. D., Schmechel, D. E., Alroy, J., and Boustany, R. M. (1996) J. Neurochem. 67, 677-683



- 2. Goebel, H. H., Mole, S. E., and Lake, B. D. (1999) in The Neuronal Ceroid Lipofuscinoses (Batten Disease) (Goebel, H. H., Mole, S. E., and Lake, B. D., eds) Vol. 33, pp. 1-211, IOS Press, Amsterdam, the Netherlands
- 3. Haltia, M. (2003) J. Neuropathol. Exp. Neurol. 62, 1-13
- 4. Vesa, J., Hellsten, E., Verkruyse, L. A., Camp L. A., Santavuori, P., Hofman, S. L., and Peltonen, L. (1995) Nature 376, 584-587
- Sleat, D. E., Donnelly, R. J., Lackland, H., Liu, C. G., Sohar, I., Pullarkat, R. K., and Lobel, P. (1997) Science 277, 1802-1805
- 6. Savukoski, M., Klockars, T., Holmberg, V., Santavuori, P., Lander, E. S., and Peltonen, L. (1998) Nat. Genet. 19, 286-288
- 7. Isosomppi, J., Vesa, J., Jalanko, A., and Peltonen, L. (2002) Hum. Mol. Genet. 11,
- 8. International Batten Disease Consortium (1995) Cell 82, 949-957
- Gao, H., Boustany, R. M., Espinola, I. A., Cotman, S. L., Srinidhi, L., Antonellis, K. A., Gillis, T., Qin, X., Liu, S., Donahue, L. R., Bronson, R. T., Faust, J. R., Stout, D., Haines, J. L., Lerner, T. J., and MacDonald M. E. (2002) Am. J. Hum. Genet. 70, 324-335
- 10. Wheeler, R. B., Sharp, J. D., Schultz, R. A., Joslin, J. M., Williams, R. E., and Mole, S. E. (2002) Am. J. Hum. Genet. 70, 537-542
- 11. Ranta, S., Zhang, Y., Ross, B., Lonka, L., Takkunen, E., Messer, A., Sharp, J., Wheeler, R., Kusumi, K., Mole, S., Liu, W., Soares, M. B., Bonaldo, M. F., Hirvasniemi, A., de la Chapelle, A., Gilliam, T. C., and Lehesjoki, A. E. (1999) Nat. Genet. 23, 233-236
- 12. Cho, S., Dawson, P. E., and Dawson, G. (2001) Eur. J. Neurol. 5, 53-55
- 13. Lovat, P. E., Di Sano, F., Corazzari, M., Fazi, B., Donnorso, R. P., Pearson, A. D. J., Hall, A. G., Redfern, C. P. F., and Piacentini, M. (2004) J. Natl. Cancer Inst. 96, 1288-1299
- 14. Persaud-Sawin, D. A., McNamara II, J. O., Rylova, S., Vandongen, A., and Boustany, R. M. (2004) Pediatr. Res. 56, 449-463
- 15. Schulz, A., Dhar, S., Rylova, S., Dbaibo, G., Alroy, J., Hagel, C., Artacho, I., Kohlschütter, A., Lin, S., and Boustany, R. M. (2004) Ann. Neurol. 56, 341-350
- 16. Hanada, K., Kumagai, K., Yasuda, S., Miura, Y., Kawano, M., Fukasawa, M., and Nishijima, M. (2003) Nature 426, 803-809
- 17. Winter, E., and Ponting, C. P. (2002) Trends Biochem. Sci. 27, 381-383
- 18. Guillas, I., Kirchman, P. A., Chuard, R., Pfefferli, M., Jiang, J. C., Jazwinski, S. M., and Conzelmann, A. (2001) EMBO J. 20, 2655-2665
- 19. Schorling, S., Vallee, B., Barz, W. P., Riezmann, H., and Oesterhelt, D. (2001) Mol. Biol. Cell 12, 3417-3427
- 20. Vallee, B., and Riezmann, H. (2005) EMBO J. 24, 730-741

- 21. Wang, H., Maurer, B. J., Reynolds, C. P., and Cabot, M. C. (2001) Cancer Res. 61, 5102-5105
- 22. Maurer, B. J., Metelitsa, L. S., Seeger, R. C., Cabot, M. C., and Revnolds, C. P. (1999) J. Natl. Cancer Inst. 91, 1138-1146
- 23. Abe, A., Inokuchi, J., Jimbo, M., Shimeno, H., Nagamatsu, A., Shayman, J. A., Shukla, G. S., and Radin, N. S. (1992) J. Biol. Chem. 111, 191-196
- 24. Amado, M., Almeida, R., Schwientek, T., and Clausen, H. (1999) Biochim. Biophys. Acta 1473, 35-53
- 25. Hennet, T. (2002) Cell. Mol. Life Sci. 59, 1081-1095
- 26. Kresse, H., Rosthoj, S., Quentin, E., Hollmann, J., Glossl, J., Okada, S., and Tonnesen, T. (1987) Am. J. Hum. Genet. 41, 436-453
- 27. Huitema, K., van den Dikkenberg, J., Brouwers, J. F. H. M., and Hlothuis, J. C. M. (2004) EMBO J. 23, 33-44
- 28. Yamaoka, S., Miyaji, M., Kitano, T., Umehara, H., and Okazaki, T. (2004) J. Biol. Chem. 18, 18688-18693
- 29. Koybasi, S., Senkal, C. E., Sundararaj, K., Spassieva, S., Bielawski, J., Osta, W., Day, T. A., Jiang, J. C., Jazwinski, S. M., Hannun, Y. A., Obeid, L. M., and Ogretmen, B. (2004) J. Biol. Chem. 279, 44311-44319
- 30. Jiang, J. C., Kirchman, P. A., Zagulski, M., Hunt, J., and Jazwinski, S. M. (1998) Genome Res. 8, 1259-1272
- 31. Mizutani, Y., Kihara, A., and Igarashi, Y. (2005) Biochem. J. 390, 263-271
- 32. Venkataraman, K., and Futerman, A. H. (2002) FEBS Lett. 528, 3-4
- 33. Lee, J. Y., Hannun, Y. A., and Obeid, L. M. (1996) J. Biol. Chem. 271, 13169 –13174
- 34. Garaventa, A., Luksch, R., Lo Piccolo, M. S., Cavadini, E., Montaldo, P. G., Pizzitola, M. R., Boni, L., Ponzoni, M., Decensi, A., De Bernardi, B., Fossati Bellani, F., and Formelli, F. (2003) Clin. Cancer Res. 9, 2032-2039
- 35. Wang, H., Charles, A. G., Frankel, A. J., and Cabot, M. C. (2003) Urology 61, 1047-1052
- 36. Veronesi, U., De Palo, G., Marubini, E., Costa, A., Formelli, F., Mariani, L., Decensi, A., Camerini, T., Rosselli Del Turco, M., Di Mauro, M. G., Miceli, R., and Sporn, M. B. (1999) J. Natl. Cancer Inst. 91, 1847-1856
- 37. Faderl, S., Lotan, R., Kantarjian, H. M., Harris, D., Van, Q., and Estrov, Z. (2003) Leukocyte Res. 27, 259-266
- 38. Batra, S., Reynolds, C. P., and Maurer, B. J. (2004) Cancer Res. 64, 5415-5424
- 39. Maurer, B. J., Melton, L., Billups, C., Cabot, M. C., and Reynolds, C. P. (2000) J. Natl. Cancer Inst. 92, 1897-1909

The CLN9 Protein, a Regulator of Dihydroceramide Synthase

Angela Schulz, Talal Mousallem, Maya Venkataramani, Dixie-Ann Persaud-Sawin, Adam Zucker, Chiara Luberto, Alicja Bielawska, Jacek Bielawski, Joost C. M. Holthuis, S. Michal Jazwinski, Lina Kozhaya, Ghassan S. Dbaibo and Rose-Mary N. Boustany

J. Biol. Chem. 2006, 281:2784-2794. doi: 10.1074/jbc.M509483200 originally published online November 22, 2005

Access the most updated version of this article at doi: 10.1074/jbc.M509483200

Alerts:

- When this article is cited
- When a correction for this article is posted

Click here to choose from all of JBC's e-mail alerts

This article cites 39 references, 11 of which can be accessed free at http://www.jbc.org/content/281/5/2784.full.html#ref-list-1