Fermented Wheat Germ Extract Inhibits Glycolysis/Pentose Cycle Enzymes and Induces Apoptosis through Poly(ADP-ribose) Polymerase Activation in Jurkat T-cell Leukemia Tumor Cells*

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The fermented extract of wheat germ, trade name Ave- mar, is a complex mixture of biologically active mole- cules with potent anti-metastatic activities in various human malignancies. Here we report the effect of Ave- mar on Jurkat leukemia cell viability, proliferation, cell cycle distribution, apoptosis, and the activity of key glyco- lytic/pentose cycle enzymes that control carbon flow for nucleic acid synthesis. The cytotoxic IC50 concentra- tion of Avemar for Jurkat tumor cells is 0.2 mg/ml, and increasing doses of the crude powder inhibitJurkat cell proliferation in a dose-dependent fashion. At concentra- tions higher than 0.2 mg/ml, Avemar inhibits cell growth by more than 50% (72 h of incubation), which is preceded by the appearance of a sub-G1 peak on flow histograms at 48 h. Laser scanning cytometry of propidium iodide- and annexin V-stained cells indicated that the growth-inhibiting effect of Avemar was consistent with a strong induction of apoptosis. Inhibition by benzoxycar- bonyl-Val-Ala-Asp fluoromethyl ketone of apoptosis but increased proteolysis of poly(ADP-ribose)-indicate caspases mediate the cellular effects of Avemar. Activi- ties of glucose-6-phosphate dehydrogenase and transke- tolase were inhibited in a dose-dependent fashion, which correlated with decreased ^13C incorporation and pentose cycle substrate flow into RNA ribose. This decrease in pentose cycle enzyme activities and carbon flow toward nucleic acid precursor synthesis provide the mechanistic understanding of the cell growth-control- ling and apoptosis-inducing effects of fermented wheat germ. Avemar exhibits about a 50-fold higher IC50 (10.02 mg/ml) for peripheral blood lymphocytes to induce a biological response, which provides the broad therapeutic window for this supplemental cancer treat- ment modality with no toxic effects.

The preventive and therapeutic potential of two natural wheat products, wheat bran and fermented wheat germ (Ave- mar), in experimental carcinogenesis has recently been de- scribed (1, 2). Although no chemical constituents are yet isolated and tested experimentally, it is likely that benzoquinones and wheat germ agglutinin in wheat germ and fiber and lipids and phytic acid in wheat bran play a significant role in exerting anti-carcinogenic effects. In a recent report utilizing intracel- lular carbon flow studies with a ^13C-labeled isotope of glucose and biological mass spectrometry (GC/MS), it was demonstrated that the crude powder of fermented wheat germ dose-dependently inhibits nucleic acid ribose synthesis primarily through the nonoxidative steps of the pentose cycle while in- creasing direct glucose carbon oxidation and acetyl-CoA utili- zation toward fatty acid synthesis in pancreatic adenocarci- noma cells (3). These metabolic changes indicate that fermented wheat germ exerts its anti-proliferative action through altering metabolic enzyme activities, which primarily control glucose carbon flow toward nucleic acid synthesis.

In vivo, Avemar has a marked inhibitory effect on metastasis formation in tumor-bearing animals (4), and this effect is attributed to its immune-restorative properties (5), which result in a decreased survival time of skin grafts and reduced cell proliferation while enhancing apoptosis. Avemar remarkably inhibits tumor metastasis formation after chemotherapy and surgery in clinically advanced colorectal cancers. Patients receiving standard surgical and chemopreventive therapies for their advanced colorectal cancers developed significantly less new metastases during the 9-month follow-up period when treated with additional 9 g/day Avemar daily (6, 7). In a recent randomized clinical study report Avemar significa- ntly prolonged (doubled) time-to-progression in high-risk melanoma patients (8). Many anticancer drugs have been shown to induce cell death through the induction of apoptosis. It is well known that apo- ptosis is a well controlled process by a programmed set of cellular events partially mediated by caspases. A large number of substrates for caspases have been reported, including poly-

* This work was supported by Grants PPQ 2000-0688-C05-03 and PPQ 2000-0688-C05-04 from the Spanish government, by NATO Col- laborative Grant LST CLG 976293, by Grant PHS M01-RR00425 from the General Clinical Research Unit, and by Grant P01-CA42710 of the UCLA Clinical Nutrition Research Unit Stable Isotope Core. 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.
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§§ The abbreviations used are: GC/MS, gas chromatography/mass spectrometry; FACS, fluorescence-activated cell sorting; G6PDH, glu- cose-6-phosphate dehydrogenase; HK, hexokinase; LDH, lactate dehy- drogenase; LSC, laser-scanning cytometry; FC, flow cytometry; PBL, peripheral blood lymphocytes; PI, propidium iodide; Z-VAD.fmk, benzoxycarbonyl-Val-Ala-Asp fluoromethyl ketone; FITC, fluorescein isothioce- nate; PARP, poly(ADP-ribose) polymerase; IDIBAPS, Institute Investi- gations Biomediques August Pi I Sunyer.
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(ADP-ribose) polymerase (PARP), a 116-kDa nucleic DNA repair enzyme that is cleaved during apoptosis by caspases-3 and -7 (9, 10). Powerful and selective reversible and irreversible apoptosis-based inhibitors are also available to better characterize and understand the mechanism(s) of how caspases regulate apoptosis. The tripeptide benzylxoycarbonyl-Val-Ala-Asp fluoromethyl ketone (Z-VAD.fmk) is a broadly used general caspase inhibitor that blocks apoptosis in many cell types, including human leukemic Jurkat T cells (10, 11).

Here we report the effect of fermented wheat germ on cell cycle regulation, proliferation, and apoptosis induction in Jurkat leukemia cell cultures. Our results confirm strong tumor growth inhibitory properties of Avemar and additionally reveal its cell cycle-regulating characteristics. Avemar decreases G6PDH and transketolase activities that are key enzymes involved in glucose conversion into the five-carbon nucleotide precursor ribose pool. Stable isotope studies indicate that Avemar is a powerful inhibitor of de novo nucleic acid synthesis. This likely is the underlying mechanism of the anti-proliferative tumor growth-controlling and apoptosis-inducing potential of fermented wheat germ in leukemia tumor cells. On the contrary, Avemar has no toxic biological effects on PBLs in the doses that affect tumor cells in an adverse manner.

MATERIALS AND METHODS

Chemicals—Ribose 5-phosphate, xylulose 5-phosphate, MgCl₂, triose-phosphate isomerase, NADH, thiamine pyrophosphate (TPP), glucose 6-phosphate, diethiothreitol, NADP⁺, propidium iodide (PI), Igepal CA-630, Ponceau S, and vincristine were purchased from Sigma Co. and Tris from ICN Pharmaceuticals Inc (Costa Mesa, CA). The Bio-Rad protein assay was purchased from Bio-Rad and the BCA protein assay from Pierce. Fetal bovine serum, RPMI 1600 medium was purchased from Invitrogen (Carlsbad, CA). Dulbecco’s phosphate-buffered saline (PBS), trypsin-EDTA and solution C (0.05% trypsin and EDTA (1:500) in PBS) were purchased from Biological Industries (Kibbutz Beit Haemek, Israel). Nitrocellulose strips were purchased from Schleicher & Schuell (Postach, Dassel, Germany). Annexin V was purchased from Bender MedSystems (Vienna, Austria), PARP from BD PharMingen cat. 66391 A and clone 7D6-6) and the secondary antibody anti-mouse immunoglobulin from DAKO (Copenhagen, Denmark). ECL was purchased from Amersham Biosciences. FK-109 Z-VAD.fmk were from Enzyme Systems Products (Livermore, CA). Avemar was kindly provided by Biromedicina, Co. (Budapest, Hungary) through a material and chemical transfer agreement.

Cell Cultures—Jurkat cells (acute lymphoid T-cell leukemia) were purchased from ATCC and cultured in RPMI 1640 medium supplemented with 10% (v/v) heat-inactivated fetal calf serum, 2 mM l-glutamine, and antibiotics: 100 units/ml penicillin and 100 μg/ml streptomycin (Invitrogen). Cells were grown in an isolated 37 °C, 5% CO₂ tissue incubator chamber. Cells were plated in 0.2–1 × 10⁶ cells/ml density for the enzyme kinetics experiments and 7.5× tissue culture flasks. For apoptosis, necrosis, and cell cycle studies cells were seeded into 8-well plates at 5 × 10⁵ cells/well density. Avemar was added to the cultures after 1 h of equilibration in the cell culture chambers after seeding. Avemar was dissolved in Dulbecco’s PBS for all experiments. Control cultures were treated with an equal volume of PBS as the Avemar and vincristine. The protein concentration of cell extracts was determined by the BCA protein assay.

Measurements of Enzyme Activities—Jurkat cells treated with increasing doses of Avemar as indicated on the x-axis; their viability and proliferation were determined by formazan dye uptake and expressed as percent of untreated control cell proliferation (A). 1 mg/ml Avemar inhibited cell proliferation in a time course study of up to 72 h in culture (B). Mean ± S.D., n = 9; *, p < 0.05; **, p < 0.01.

Cell Viability Assay—Cell number was determined by the MTT (3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide) assay (13). 20,000 Jurkat cells per well were incubated in 96-well plates in the presence or in the absence of Avemar at different concentrations. Vinristine was used as a positive control for apoptosis induction. The blue MTT formazan precipitate was dissolved in 100 μl of Me₂SO, and the absorbance values at 550 nm were determined on a multiwell plate reader. For peripheral blood cells, 500,000 cells were seeded in 12-well plates in the presence or in the absence of Avemar at different concentrations. Viability was estimated by a MultizisserIII Coulter (Beckman Coulter, Fullerton, CA) to count the cells and by FACS analysis adding 15 μg/ml PI (Sigma Co.) staining method without cell permeabilization. The fluorescence of cells was analyzed by flow cytometry using an Epics XL flow cytometers (Beckman Coulter, Fullerton, CA). Only non-viable cells are PI positives as indicated by previous studies (14).

Assessment of Apoptosis by Flow Cytometry and LSC—Jurkat cells after Avemar treatment were washed once in binding buffer (10 mM HEPES, sodium hydroxide, pH 7.4, 140 mM sodium chloride, 2.5 mM calcium chloride) and resuspended in the same buffer at 10⁶ cells ml⁻¹ in the presence of 0.5 μl of annexin V-FITC. After 30 min of incubation at room temperature, PI was added at 0.05 μg ml⁻¹ (11). The fluorescence of cells was analyzed by FC and LSC. Approximately 3 × 10⁶ cells were tested for each histogram for FC and 1500 cells for LSC.

PARP Gel Electrophoresis and Immunoblotting of PARP—To analyze PARP, SDS-page electrophoresis (15) and immunoblotting were performed as previously described (16). Briefly, 30 μg of the protein extract was used on an 8% polyacrylamide gel and transferred to Protein membranes (Schleicher & Schuell, GmbH, Postach, Dassel, Germany). Monoclonal antibodies either against PARP were used at a 1:1000 dilution. As a control of protein loading the blot membrane was stained with Red Ponceau. The reaction was visualized with a secondary antibody (anti-mouse immunoglobulin, DAKO) conjugated to horseradish peroxidase diluted 1:1000 in bovine serum albumin/Tween-20/PBS and the enhanced chemiluminescence (ECL) detection kit (Amersham Biosciences). PARP immunoblotting was performed after 48 h of incubation with the Avemar and vincristine. The protein concentration of cell extracts was determined by the BCA protein assay.

Measurements of Enzyme Activities—Jurkat cells treated with increasing doses of Avemar were lysed in 1 ml of 20 mM Tris buffer (pH 7.5) containing 1 mM diethiothreitol and 0.2 mM phenylmethylsulfonyl fluoride, 1 mM K-EDTA, 0.2 g/liter Triton X-100, and 0.2 g/liter sodium deoxycholate. Cell extracts were stored at −20 °C for 24 h. The homogenates were then deproteinized in an ice bath, sonicated in a Branson 2500 cell disintegrator for 5 min, ultracentrifuged at 100,000 × g for 1 h, and the supernatant used for enzyme activity assays as described below.

Transketolase (EC 2.2.1.1) activity was determined using the enzyme-linked method of De La Haba et al. (17). 1-ml aliquots of transketolase-free buffer were measured in spectrophotometry cuvettes containing 50 mM Tris-HCl, pH 7.6, 2 mM ribose 5-phosphate, 1 mM xylulose 5-phosphate, 5 mM MgCl₂, 0.2 units/ml triose-phosphate isomerase/glyceraldehyde-3-phosphate dehydrogenase, 0.2 mM NADH, and 0.1 mM thiamine pyrophosphate. The transketolase reac-

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**FIG. 1.** Jurkat leukemia cell proliferation in response to Avemar treatment. Jurkat cell cultures were treated with increasing doses of Avemar as indicated on the x-axis; their viability and proliferation were determined by formazan dye uptake and expressed as percent of untreated control cell proliferation (A). 1 mg/ml Avemar inhibited cell proliferation in a time course study of up to 72 h in culture (B). Mean ± S.D., n = 9; *, p < 0.05; **, p < 0.01.
tation was initiated by the addition of 25 and 50 µl of cell extract at 37 °C. The oxidation of NADH, which is directly proportional to transketolase activity, was measured by the decrease in 340-nm absorbance. Transketolase activity is expressed as nmol/min/million cells.

Glucose-6-phosphate dehydrogenase (G6PDH; EC 1.1.1.49) activity was measured as described by Tian et al. (18). Briefly, cuvettes were prepared with 50 mM Tris-HCl, pH 7.6 buffer, containing 10 mM glucose-6-phosphate and 0.5 mM NADP. Reactions were initiated by the addition of 25 and 50 µl of cell extract at 37 °C. The reduction of NADP, which is directly proportional to G6PDH activity, was quantified by the increase in 340-nm absorbance, and G6PDH activity is expressed as nmol/min/million cells.

Lactate dehydrogenase (LDH; EC 1.1.1.27) activity was measured as described by Mommensen et al. (19). The assay medium for lactate dehydrogenase contained 50 mM Tris-HCl buffer, pH 7.6, 0.2 mM NADH, and 5 mM pyruvate (omitted for control). The oxidation of NADH, which is directly proportional to lactate dehydrogenase activity, was measured by the decrease in 340-nm absorbance. LDH activity is expressed as nmol/min/million cells.

Hexokinase (HK; EC 2.7.1.1) activity was measured by the enzyme-linked method of Grossbard and Schimke (20). Briefly, cuvettes were prepared with a 50 mM Tris-HCl, pH 7.6 buffer, containing 10 mM glucose, 1 mM NADP, 2 mM ATP, 10 mM magnesium chloride, and 1 unit of G6PDH. Reactions were initiated by the addition of 50 and 100 µl of cell extract at 37 °C. The reduction of NADP, which is directly proportional to HK activity, was quantified by the increase in 340-nm absorbance, and HK activity is expressed as nmol/min/million cells.

Stable Isotope Incorporation into RNA Ribois—In order to measure actual substrate carbon flow in the pentose cycle and glycolysis, which are controlled by the enzymes listed above, we utilized stable isotope-based metabolic profiling as introduced for drug effect studies in cancer (21). Jurkat cell continuous S phase-independent nucleic acid synthesis rates were measured by the incorporation of [1,2-13C2]glucose into RNA ribose as the single tracer and biological mass spectrometry. 13C label accumulation into RNA was determined by measuring the molar enrichment (ME) of ribose using chemical ionization methods, which is capable of determining both total activity (Σm/s) and positional distribution of 13C labels in nucleic acid ribose as described previously (22, 23).

Stable Isotope Incorporation into Lactate—Lactate from the cell culture media (0.2 ml) was extracted by ethyl acetate and derivatized to its propylamine-HFB form. The m/z 328 (carbons 1–3 of lactate, chemical ionization) ion cluster was monitored for the detection of m/z 1 (recycled lactate through the pentose cycle) and m/z 2 (lactate produced by glycolysis) for the estimation of the pentose cycle activity relative to glycolysis (23).

Gas Chromatography/Mass Spectrometry—Mass spectral data were obtained on the HP5973 mass selective detector connected to an HP6890 gas chromatograph. The settings were as follows: GC inlet, 230 °C; transfer line, 280 °C; MS source, 230 °C; MS Quad, 150 °C. An HP-5 capillary column (30-m length, 250-μm diameter, 0.25-μm film thickness, Supelco) was used for ribose analysis at the ion cluster m/z 256 and for lactate analysis (23).

Data Analysis and Statistical Methods—Experiments in vitro were carried out using three cultures each time for each treatment regimen and then repeated twice. Mass spectral analyses were carried out by three independent automatic injections of 1-µl samples by the automatic sampler and accepted only if the standard sample deviation was less than 1% of the normalized peak intensity. Enzyme activity measurements were determined after correction for total protein content in cell extract. Statistical analysis was performed using the parametric unpaired, two-tailed independent sample Student’s t test with 99% confidence intervals (μ ± 2.58s) and p < 0.01 was considered to indicate significant differences in glucose carbon metabolism and enzyme activities with increasing doses of Avemar. Because of the human cell line involved, a clearance was obtained from the Institutional Review Boards of both Harbor-UCLA and The University of Barcelona for the use of these commercially available for the experiments reported.

RESULTS

For the present report, Jurkat lymphoid T-cell leukemia cells were treated with increasing amounts of Avemar for either 48 or 72 h in order to estimate the growth regulating effects of this natural anti-cancer nutritional supplement through cell cycle modulation, apoptosis induction, metabolic enzyme activity changes as well as substrate flow measure-ments. Avemar doses of 10 mg/ml (stock) and its serial dilutions were selected for the study because the effective oral dose of Avemar that inhibits tumor metastasis formation is 9.0 g/day, which is equivalent to an estimated plasma concentration of 0.5 and 1 mg/ml in an average (70 kg) weight patient.

Cytotoxic Effects of Avemar on Jurkat cells—Avemar induced a dose-dependent decrease in vital formazan dye accumulating cells after 72 h of treatment, ranging from 0 to 10 mg/ml (Fig. 1A). The mean IC50 of Avemar was 0.23 ± 0.03 mg/ml. The cytotoxicity of Avemar on Jurkat cells was studied using a time course experiment. A significant increase in cell death by formazan exclusion was detected as early as 24 h with 1 mg/ml Avemar treatment (Fig. 1B). The mean IC50 of vincristine as a positive control was 0.18 ± 0.02 μM. Avemar exhibited about 50-fold higher IC50 (10.02 mg/ml) for PBLS to induce biological responses.

Cell Cycle—In control cultures the cell cycle pattern remained constant over time; the percentage of cells in the G0/G1 phase: 40, 39, and 42%; S phase: 35, 39, and 34%; and G2/M phase: 25, 23, and 23% after 24, 48, and 72 h, respectively (Fig. 2). A complete alteration of the cell cycle patterns became evident as shown in Fig. 2 by the gray arrows after 48 and 72 h with 0.5 mg/ml or higher Avemar concentrations. At concentrations of 0.7 and 1 mg/ml Avemar, even after 24 h, a broad peak appeared in the sub-G1 region with a significant decrease in the S cycle phase. The sub-G1 region is indicative of apoptosis (Fig. 2, black arrows). Although lower concentrations of Avemar (0.1 and 0.3 mg/ml) induced only minor changes in the cell cycle distribution of Jurkat cells, they were still effective in controlling cell growth as there was a significant decrease in formazan-accumulating Jurkat cells as shown in Fig. 1A.

Induction of Apoptosis—Avemar triggered prominent apoptosis at 0.5 mg/ml dose after 72 h of culturing as demonstrated by FACS analysis. Increasing doses of Avemar induced more prominent apoptosis, which also appeared earlier (Fig. 3A). In order to discriminate between late apoptotic and necrotic cells, we investigated PI and annexin V-FITC positive cells using LSC analyses. We observed that all cells with PI/FITC + char-

![Fig. 2. Jurkat leukemia cell cycle changes in response to Avemar treatment.](Image)
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Fig. 3. Jurkat leukemia cell apoptosis in response to Avemar treatment. A, Jurkat cell cultures were treated with increasing doses of Avemar as indicated on the x-axis, and the number of apoptotic Jurkat cell was determined using flow cytometry after PI and annexin V staining. 24-hour treatment is shown with open bars, 48-hour treatment with light gray bars, and 72-hour treatment with dark gray bars. It can be depicted that Avemar induced a time- and dose-dependent increase in apoptosis in Jurkat cells in culture. Time dependence is clear at the 0.5 and 1 mg/ml dose treatments. Mean ± S.D., n = 9; *, p < 0.05; **, p < 0.01. B, percentage of annexin V positive cells after 72 h of treatment with and without the caspase inhibitor Z-VD-fmk (100 μM) of Avemar-treated cultures (1 mg/ml). Mean ± S.D., n = 5; **, p < 0.01. Positive controls were treated with 1 μM of staurosporin (SSP). C, Western blots of extracts prepared from cells treated for 48 h with the indicated concentrations of Avemar (0 control; 0.3, 0.5, or 0.7 mg/ml) and probed with anti-PARP antibody. The position of native PARP (116 kDa) and the proteolytic fragment (85 kDa) is indicated here.

Fig. 4. Jurkat leukemia cell apoptosis and necrosis in response to Avemar treatment using LSC. Jurkat cell cultures were treated with 1 mg/ml Avemar (72 h), and the formation of apoptotic and necrotic Jurkat cell figures was determined using PI and Annexin V-FITC staining. The majority (64.5%, right bottom quadrant) of Jurkat cells exhibited early apoptosis as indicated by the limited nuclear fragmentation. Late apoptosis/necrosis was present in about 30% (right upper quadrant) of Jurkat cells with advanced nuclear fragmentation and limited staining, while the frequency of normal cells dropped to 5.5% as seen in the left bottom quadrant of the LSC screen (n = 6).

13C Label Accumulation in Lactate—We observed a decrease in m2 and m1 13C label in lactate in Avemar-treated Jurkat cells, which is indicative of decreased glucose uptake and glycolysis. Overall carbon flux in the pentose cycle relative to glycolysis showed a dose-dependent non-significant increase in Jurkat cells after 2 days of Avemar treatment after 0.1 and 0.5 mg/ml treatments. At the dose of 1 mg/ml Avemar treatment the pentose cycle showed a rapid 22% decrease relative to glycolysis, as indicated by decreased m1/m2 13C ratios in lactate (Table 1).

13C Label Accumulation in RNA Ribose—In order to estimate nucleic acid precursor synthesis measurements of the molar enrichment of RNA ribose with 13C from glucose was...
transketolase activities (Figs. 5 and 6).

Mean ± S.E.; n = 9; *, p < 0.05; **, p < 0.01.

FIG. 5. Jurkat leukemia cell G6PDH (A) and transketolase (B) enzyme activities in response to 48 and 72 h of Avemar treatment. Avemar inhibited both G6PD and transketolase in a dose- and time-dependent manner. Mean ± S.E.; n = 9; *, p < 0.05; **, p < 0.01.

FIG. 6. Jurkat leukemia cell hexokinase (A) and lactate dehydrogenase (B) enzyme activities in response to 48 h of Avemar treatment. Avemar inhibited both enzymes in Jurkat cells in a dose-dependent manner. Mean ± S.E.; n = 9; *, p < 0.05; **, p < 0.01.

carried out because ribosomal and messenger RNAs are continuously synthesized in tumor cells regardless of their proliferative response, cell cycle alterations and apoptosis formation in response to anti-carcinogenic treatments. 

...Apoptosis is a natural response of the host to carcinogenesis. It is a genetically programmed process that leads to the elimination of potentially oncogenic cells in the body. This study investigates the complex responses to Avemar treatment, a potent natural fermented wheat germ extract with anticarcinogenic properties, of Jurkat T-progeny leukemia cells in culture. Using flow and laser scanning cytometry techniques, direct enzyme activity measurements, carbon substrate flow measurements with a 13C-labeled glucose tracer has enabled us to study a broad range of cellular response mechanisms, such as cell cycle progression, apoptosis, cell proliferation, and their dose-response to this cancer growth-modifying agent. Activity changes of four important metabolic enzymes involved in direct glucose oxidation (G6PDH), non-oxidative glucose utilization (transketolase) toward nucleic acid synthesis, glycolysis (LDH), and glucose activation (HK) are herein also reported. Our studies revealed profound differences and a dose-dependent response of Jurkat leukemia cells that directly affected metabolic enzyme activities, metabolic pathway substrate flow, apoptosis formation, and cell proliferation in response to Avemar. It has previously observed that G6PDH inhibition leads to an increase in apoptosis formation in tumor cells of various origins (26, 27). In contrast, Avemar treatment according to our results is about 50× less effective in peripheral blood lymphocytes in inducing biological effects, which provides a comfortable therapeutic window for Avemar to apply in patients as a supplemental treatment modality with minimal or no toxic side effects.

It has been proved that the flip-flop of phosphatidylserine from the inner to the outer plasma membrane leaflet of the cell is a fundamental characteristic that differentiates apoptosis from necrosis (28). This early phenomenon during the apoptotic process is followed by caspase activation, which can specifically be inhibited and the fact that this inhibitor effectively inhibited Avemar-induced phosphatidylserine externalization demonstrated the involvement of caspases in mediating the biological apoptosis-inducing effects of Avemar. Furthermore, we detected a cleavage of PARP during Avemar-induced apoptosis in Jurkat cells, which more specifically points to the involvement of caspase-3 in the cascade that mediates wheat germ-induced apoptosis. Based on these molecular findings our data also indicate that the mechanism of how Avemar mitigates metastasis also involves decreasing cell motility.

It has recently been demonstrated that Avemar induces profound metabolic changes in cultured MIA pancreatic adenocarcinoma cells using the [1,2-13C2]glucose isotope as the single tracer and biological gas chromatography/mass spectrometry. It was concluded that Avemar controls tumor propagation primarily through the regulation of glucose carbon redistribution between cell proliferation- and cell differentiation-related macromolecules in MIA cells (3). In the present study we again applied stable isotope-based dynamic metabolic profiling as a model for measuring metabolic pathway control characteristics (29) by demonstrating a dose-dependent decrease in substrate carbon flow toward nucleic acid precursor ribose synthesis and metabolic enzyme activities (G6PDH, transketolase, HK, and LDH) in Jurkat leukemia cells treated with comparable doses of Avemar. Indeed, Jurkat cells also responded with decreased carbon flow through the pentose cycle toward nucleic acid synthesis and in this study the significant, dose-dependent decrease of G6PDH and transketolase are also demonstrated. It is likely that decreased oxidative ribose synthesis in response to Avemar treatment in Jurkat cells is not able to supply the...
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**Table I**

Lactate production of Jurkat cells in response to increasing doses of Avemar treatment after 48 h of culture. Lactate isomers derived from [1,2-\(^{13}C\)\(_2\)] glucose based on glycolysis (m2) or direct glucose oxidation (m1). PC represents the pentose cycle, and it is defined as a percentage of direct glucose oxidation/recycling of the glycolytic flux or m1/m2 ratios in the released lactate into the culture media. S.E. in all cases was lower than 0.1% of the mean value.

<table>
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<th>Lactate</th>
<th>m0</th>
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<th>m2</th>
<th>m1/m2</th>
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<tr>
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<td>0.006</td>
<td>0.1849</td>
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<td>0.1723</td>
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<td>0.1 mg/ml</td>
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<tr>
<td>0.5 mg/ml</td>
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<td>0.0675</td>
<td>0.0252</td>
<td>0.83%</td>
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<tr>
<td>1 mg/ml</td>
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<td>0.0017</td>
<td>0.0675</td>
<td>0.0252</td>
<td>0.83%</td>
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**Table II**

Effect of Avemar on RNA ribose synthesis. Ribose isomers obtained from the experiment with glucose label are shown as m0, m1, m2, m3, and m4, which represent unlabeled, 1, 2, 3, and 4 \(^{13}C\) substitutions assembled by specific synthesis pathways for nucleic acid ribose synthesis. \(\Sigma m_n\) represents the molar enrichment of \(^{13}C\) for each condition. S.E. in all cases was lower than 0.1% of the mean value.

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<th>m2</th>
<th>m3</th>
<th>m4</th>
<th>(\Sigma m_n)</th>
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<td>0.2139</td>
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<td>0.1844</td>
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<tr>
<td>0.5 mg/ml</td>
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REFERENCES

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