Aloe-emodin Is a New Type of Anticancer Agent with Selective Activity against Neuroectodermal Tumors

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Abstract

Here we report that aloe-emodin (AE), a hydroxyanthraquinone present in Aloe vera leaves, has a specific in vitro and in vivo antineuroectodermal tumor activity. The growth of human neuroectodermal tumors is inhibited in mice with severe combined immunodeficiency without any appreciable toxic effects on the animals. The compound does not inhibit the proliferation of normal fibroblasts nor that of hemopoietic progenitor cells. The cytotoxic mechanism consists of the induction of apoptosis, whereas the selectivity against neuroectodermal tumor cells is founded on a specific energy-dependent pathway of drug incorporation. Taking into account its unique cytotoxicity profile and mode of action, AE might represent a conceptually new lead antitumor drug.

Introduction

With the aim of developing novel anticancer drugs characterized by selective targeting and low toxicity for dividing normal host tissues, we devoted our attention to a number of natural compounds that have traditionally been used to treat a variety of diseases for hundreds of years (1–3). We assayed only those natural compounds that have already been proven to be nontoxic, and we evaluated their efficacy against highly malignant tumors that are not normally included in the classical screening assays, i.e., pPNET, Ewing’s sarcoma, and neuroblastoma. The last of these is the most common solid extracranial tumor in infants, accounting for 10% of all childhood cancers. At the time of diagnosis, ~50% of affected children have disseminated neuroblastoma disease with a very poor prognosis that has remained unchanged in the last 3 decades (4, 5). Our study analyzed the cytotoxic potential of AE, a hydroxyanthraquinone (Fig. 1A) naturally present in the leaves of Aloe vera (6, 7). This report describes the selective in vitro and in vivo killing of neuroectodermal tumor cells by AE, the anticancer activity of which is based on apoptotic cell death, promoted by a tumor cell-specific drug uptake process that may offer opportunities for novel anticancer agents.

Materials and Methods

Drugs. AE was purchased from Sigma-Aldrich (Milan, Italy); it was dissolved in DMSO to reach a concentration of 200 mM and stored at −20°C. The compound was diluted in the appropriate medium immediately before use. AE is a fluorescent compound with a maximum excitation wavelength at 410 nm and a maximum emission wavelength at 510 nm. Aloin was a generous gift of MacFarlan Smith Ltd. (Edinburgh, Scotland). It was dissolved by slight warming in saline solution at the working concentration.

Mice. Female SCID mice were purchased from Charles River Italia (Calco, Italy). The animals were kept in a pathogen-free colony, in microisolators, and were fed sterile pellets and sterile water ad libitum. During the experiments, mice were tested for the presence of gross sensory or motor neurological disturbances: the geotaxic response and righting reflexes, forelimb placement reflex, and climbing responses (8). Hematological assessment was performed by Coulter MAXM. The animals were scored twice a week for body weight and daily for fecal emission. The mice were age matched (6–8 weeks of age) at the beginning of each experiment.

Cell Culture. Neuroblastoma cells (IMR-32, IMR-5, A8, and SJ-N-KP), pPNET cells (TC32), Ewing’s sarcoma cells (TC106), T-cell leukemia cells (CEM), and vinblastine-resistant cells (CEM VBL), colon adenocarcinoma cells (LoVo 109), and doxorubicin-resistant cells (LoVo DX) were cultured in RPMI 1640 supplemented with 25 mM HEPES buffer and with 2 mM l-glutamine (all from Life Technologies, Ltd., Paisley, Scotland). The culture of CEM VBL cells was supplemented with 10 μg/ml vinblastine (Lilly France, Saint-Cloud, Paris, France), and the culture of LoVo DX cells was supplemented with 0.1 μg/ml doxorubicin (Pharmacia, Milan, Italy). Cervix epithelioid carcinoma (HeLa) and human lung fibroblast (MRC5) cells were cultured in DMEM supplemented with 25 mM HEPES buffer and with 2 mM l-glutamine (all from Life Technologies, Ltd.). All culture medium was supplemented with 10% heat-inactivated fetal bovine serum (Sigma-Aldrich, Milan, Italy), 100 units/ml penicillin, and 100 μg/ml streptomycin (Sigma-Aldrich, Irvine, United Kingdom). All cell lines were grown at 37°C with 5% CO2 humified atmosphere.

In Vitro Cytotoxicity. The cytotoxic activity of AE was determined in exponentially growing cells in complete medium over 72 h. The cells were seeded in 12 wells/plate 24 h before the treatment: monolayer cells were plated at a density of 5–7 × 104 cells/well, and suspension cells were plated at 40 × 104 cells/well. AE was added to the experimental final concentration, and cells were counted 72 h later using the trypan blue exclusion assay. All of the experiments were conducted at least in triplicate.

Hemopoietic Progenitors and Neuroblastoma Colony Assay. MNCs from BM aspirates and CB samples and from neuroblastoma cell lines (SJ-N-KP and A8) were cultured in methylcellulose medium supplemented with a combination of recombinant colony-stimulating factors (Stem Cell Technologies, Vancouver, British Columbia, Canada). Cells were plated in triplicate at the concentration of 5 × 103/ml for BM- and CB-MNC, and 1 × 105 for NB cells, in 35-mm-diameter dishes (Becton Dickinson, Franklin Lakes, NJ) and incubated at 37°C in a 5% CO2 humified atmosphere. MNC and NB cell lines were cultured in the absence or in the presence of different concentrations of AE. On day 14 of culture, the number of CFU-GM and neuroblastoma colonies was counted with an inverted microscope (Leitz-Diavert). All of the experiments were conducted at least three times.

Fluorescence-activated Cell Sorting Analysis. Neuroblastoma (SJ-N-KP), colon adenocarcinoma (LoVo 109), and cervix epithelioid carcinoma (HeLa) cell lines (1 × 106) were cultured for different time periods in the presence of AE or drug-free medium. Cells were harvested, washed twice with PBS, and fixed with cold 70% ethanol at 4°C. After centrifugation of the
samples, propidium iodide (50 μg/ml in PBS) and RNase were added to the pellet for 20 min at 37°C to determine the effect of AE on the cell cycle dynamics. DNA fluorescence was measured by flow cytometry (EPICS XL; Coulter, Miami, FL) analysis according to a published method (9). To determine drug uptake, SJ-N-KP, LoVo 109, and HeLa cells were cultured in the presence of 25 μM of AE or in drug-free medium at 37°C or at 4°C or in presence of NaN₃, for 24 h and then analyzed by flow cytometry (10).

Two-Photon Excitation Microscopy. Neuroblastoma (IMR5), colon adenocarcinoma (LoVo 109), and cervix epithelioid carcinoma (HeLa) cell lines were seeded on microscope coverslips in 12-well plates and cultured with drug-free medium 24 h before treatment. Then AE was added at different concentrations. At different time points, cells were washed twice with PBS and examined by means of “fluorescence two-photon confocal microscopy.” Optical sections were acquired with a TPE architecture described in detail elsewhere (11).

Transmission Electron Microscopy Analysis. Cells were cultured with different concentrations of AE or with drug-free medium. At 24 and 48 h cells were scraped, washed twice in PBS, and fixed overnight at 4°C in 3% glutaraldehyde in 0.1 m sodium cacodylate buffer (pH 6.9) and then processed according to Ciman et al. (12). Ultrathin sections, cut with an ultramicrotome (Ultracut; Reichert-jung), were observed with the transmission electron microscope (TEM 300; Hitachi) operating at 75 kV.

Results

Cytotoxic Activity of AE in Cell Culture. The cytotoxic potential of AE was evaluated on exponentially growing cells over a period of 72 h. As shown in Fig. 2A, AE displayed a specific dose-dependent cytotoxic effect on neuroblastoma, pPNET, and Ewing’s sarcoma cells. Indeed, the growth of the neuroectodermal tumor cell lines was specifically inhibited, and ED₅₀ (half-maximal effective doses) ranged between 1 and 13 μM (neuroblastoma and Ewing’s sarcoma, respectively). Conversely, epithelial tumors, such as cervix carcinoma and colon carcinoma cells, and also T-cell leukemia cells and normal fibroblasts, were almost refractory to the treatment with AE (Fig. 2B). ED₅₀ for these cell lines ranged from 40 μM for cervix carcinoma cells (HeLa) to 100 μM for T-cell leukemia cells (CEM). To determine whether AE might have inhibited the clonogenic activity of the hemopoietic progenitors and neuroectodermal tumor cell lines, cells were seeded into methylcellulose medium and monitored for colony formation. As shown in Fig. 2C, AE had no significant inhibitory activity on the growth of CFU-GM after 14 days of treatment. The colony growth was only partially reduced at high concentrations of AE, with ED₅₀ of 80 and 120 μM, respectively, for BM- and CB-derived CFU-GMs. In contrast, the colony-forming activity of neuroblastoma cells (SJ-N-KP) was inhibited at a much lower concentration of AE (ED₅₀ of 7 μM).
Specific Uptake of AE by Neuroectodermal Tumor Cell Lines and Intracellular Localization. To explain the specific cytotoxic activity of AE against neuroectodermal tumor cell lines, we evaluated the cellular uptake of this compound by different cell lines, exploiting the drug’s relatively intense green fluorescence (see “Materials and Methods”). As shown in Fig. 3, A and B, AE treatment of SJ-N-KP and HeLa cells at 37°C gave rise to an intense fluorescence emission only from the former, a result suggestive of AE selective cellular uptake. Conversely, when SJ-N-KP cells were exposed to AE at 4°C, no fluorescence emission was detected (Fig. 3C). With colorectal carcinoma (LoVo 109) and T-cell leukemia (CEM) cell lines, lack of drug uptake was also observed at 37°C (data not shown).

To determine whether drug accumulation depended on the energized status of the cells, ATP pools were depleted by a 2-h preincubation with 1 mM NaN₃ in glucose-free medium (13). Fig. 3D shows that this led to a significant decrease in intracellular fluorescence emission by SJ-N-KP cells.

Microscopic observation with TPE modality showed the relative amount of AE uptake and provided three-dimensional information on the drug’s intracellular fate in sensitive cells. After 24 h of incubation, AE was present in the cytoplasm of neuroblastoma cell lines in a spotty fashion inside endosomes (Fig. 3E), with an intensity of fluorescence of 8.8 arbitrary units. A barely detectable fluorescence emission (1.9 arbitrary units) was recovered from HeLa (Fig. 3F), LoVo 109, and MRC5 cells maintained under the same experimental conditions.

Nuclear localization of AE was readily appreciable in the sensitive cells as early as 1 h after treatment. In this case, because of the intrinsic fluorescence quenching of the anthraquinone on interaction with DNA (14), drug detection was achieved by counterstaining nuclei with propidium iodide (data not shown).

Effects of AE on Cell Cycle and Apoptosis. On the basis of its chemosensitivity profile, neuroblastoma was selected as a prototype chemosensitive tumor for exploring the molecular requirements for AE-triggered cell death. Changes in SJ-N-KP cellular proliferation (DNA content and distribution) during treatment with AE were monitored by flow cytometry over a period of 48 h, an interval sufficient for SJ-N-KP cells to complete a cell cycle. As shown in Fig. 4, A and B, after 24 h of treatment a relevant proportion of the cells remained in the G₂-M phase of the cycle (20%). After 48 h, a sub-G₀ peak (60%) was observed, suggestive of the presence of apoptotic cells with fragmented DNA (Fig. 4C). Typical morphological features of apoptotic cell death, with cell shrinkage, membrane blebbing, and nuclear fragmentation, were also exhibited by most AE-treated cells at TEM analysis. A representative picture of this phenomenon is shown in Fig. 4, D and E.

In Vitro Inhibition of Neuroblastoma Growth by AE. The potential of AE as an antineoplastic agent in vivo was assessed in a murine model system. Mice with SCID were injected s.c. with human neuroblastoma cells (IMR5) and immediately treated with AE at a dose of 50 mg/Kg/day (the highest concentration compatible with an acceptable toxicity. Lack of toxicity in combination with significant antitumor effects of AE against neuroectodermal tumors and inhibits human neuroectodermal tumor growth in an animal model with no evidence of acute or chronic toxicity. Lack of toxicity in combination with significant antitumor...
activity results in a favorable therapeutic index. Our study describes the discovery of AE as a new type of anticancer agent possessing an unprecedented cytotoxic mechanism. A specific intracellular uptake was responsible for the selective toxicity of AE against human neuroectodermal tumor cells. Measurements performed at 37°C showed a high level of incorporation of the compound into the tumor cells of neuroectodermal origin but not into other tumor cells. When neuroblastoma cells were exposed to the drug at 4°C, however, AE uptake was completely abolished. A similar result was obtained when the cells were ATP depleted, indicating that drug influx was an energy-
dependent process. The nature of this process, apparently unique to neuroectodermal tumor cells, is not related to passive diffusion, nor is it likely to depend on membrane partition phenomena, which occur only at 37°C and in fully energized cells. On the other hand, when the chromophore structure of AE was modified by the presence of a hydrophilic glycosidic residue, as in aloin, a natural glucoside whose AE is the aglycone (Fig. 1B), no incorporation occurred and no cytotoxicity was exhibited in susceptible cells (data not shown). Our data would thus point to a receptor-mediated recognition process behind selective AE uptake.

Morphological observations of AE-treated neuroectodermal tumor cells revealed the typical features of apoptosis, an effect produced by many anticancer drugs (18, 19). The apoptotic phenomenon was further confirmed by the detection of a sub-G₀ peak, at flow cytometry, after 48 h of treatment. The induction of programmed cell death might be related to induction of DNA damage, as suggested by cytotoxic and nuclear localization time courses.

Because of the nonselective mechanisms of action of common anticancer drugs, a high incidence of potentially severe toxicity must be tolerated for effective doses to be administered (20). In this regard, it is noteworthy that AE does not inhibit the proliferation of hematopoietic progenitors. In fact, the colony-forming activity of CFU-GM from BM and CB is not suppressed at concentrations even a hundred times higher than those inhibiting neuroectodermal tumor cell growth and clonogenic activity. This finding is at variance with the behavior of all anticancer agents in use to date and points to a novel selective mechanism residing in specific tumor targeting by a naturally available compound.

Taking into account its unique in vitro and in vivo antitumor activity, selective toxicity, and cellular pharmacokinetics, AE can be viewed as a conceptually new lead anticancer agent that might contribute to the development of targeted nontoxic drugs. Preclinical development is clearly warranted and is currently under way to further confirm this conceptually new lead anticancer agent that might contribute to the development of targeted nontoxic drugs. Preclinical development is clearly warranted and is currently under way to further confirm this.

**References**

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