4-aminopyridine Induces Apoptosis of Human Acute Myeloid Leukemia Cells via Increasing $[Ca^{2+}]_i$ Through P_2X_7 Receptor Pathway

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Key Words

4-aminopyridine • Acute myeloid leukemia • Apoptosis • Mitochondria • Purinergic receptors

Abstract

4-AP, a voltage-gated potassium channel blocker, was identified to exert critical pro-apoptotic properties in various types of cancer cells. The present study aims to explore the effect of 4-AP on the apoptosis of human AML cells and the underlying mechanism. We found 4-AP inhibited the proliferation and induces apoptosis in both AML cell lines and primary cultured human AML cells. The apoptosis of AML cells after 4-AP treatment was further confirmed by the disruption of mitochondrial membrane potential (MMP) and activation of caspase 3 and 9. 4-AP inhibited Kv currents in NB₄, HL-60 and THP-1 cells. Furthermore, 4-AP induced significant increment in $[Ca^{2+}]_i$, which were inhibited by KN-62, a specific blocker of P_2X_7 receptors. KN-62 also abrogated 4-AP induced apoptosis. Knockdown of P_2X_7 receptor by small interfering RNA blocked the effect of 4-AP. Conclusively, this study indicated that 4-AP promotes apoptosis in human AML cells via increasing $[Ca^{2+}]_i$ through P_2X_7 receptor.

Introduction

Acute myeloid leukemia (AML) is a malignancy of the myeloid lineage of white blood cells, characterized by clonal expansion of abnormal myeloid progenitor cells that accumulate in the bone marrow and interfere with normal hematopoiesis. A recent study reported that the 5-year survival rate of those diagnosed with AML age = 55 years was 23%, whereas the corresponding rate for those age >55 years was 11% [1, 2]. Even when the most aggressive therapeutic approaches are applied early, the cure rate remains at 35% to 40% [3-6] and <10% of all AML patients survive past 3 years [7]. Thus, there is an urgent need for the discovery of novel therapeutic agents for AML.

The aim of anti-cancer therapy is to induce apoptosis of tumor cells. Studies demonstrated that 4-aminopyridine (4-AP), one of the most commonly used K⁺ channel inhibitors, suppresses proliferation and induces apoptosis in various types of cancer cells [8-12], such as neuroblastoma cells [8], NF1 Schwann cells [9], human melanoma cells [10], LNCaP human prostate cancer cells [11], and malignant astrocytoma cell lines [12]. These anti-cancer activities were mostly attributed to its inhibition on voltage-gated potassium channels.

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Recently, 4-AP was linked to the activation of calcium influx and apoptosis [13-15]. Guse et al. showed that 4-AP could cause a transient increase in $[Ca^{2+}]_i$ [14], which act as a common mediator of cell death [16] and a signal transducer of apoptosis [17]. Kim et al. showed that 4-AP induced apoptosis in HepG₂ human hepatoblastoma cells by activating Ca^{2+} influx pathway through nonselective cation channel NSCC induced by membrane potential change [15]. 4-AP was further confirmed to induce increases in intracellular calcium influx through modulation of the activity of purinergic cationic channels in human mononuclear cells [18].

Currently, the effect of 4-AP in AML is largely unknown, except that Xu B et al demonstrated that 4-AP induces G₁ arrest in the human myeloblastic ML-1 cell line [19]. As ML-1 cell line is derived from a patient diagnosed as T-cell malignant lymphoma (Stage IV) terminating in AML [19], it can not represent the general features of AML. Therefore, in this study we investigated the effect of 4-AP on AML cell lines and primary AML cells, and the involvement of P₂X₇ receptor mediated calcium influx in this process. We found 4-AP induces apoptosis of the AML cell lines NB₄, HL-60 and THP-1 as well as primary AML cells, which were prevented by inhibition of P₂X₇ pore mediated $[Ca^{2+}]_i$ increment.

Materials and Methods

Cell culture

THP-1 (Permanent human cell lines representing acute monocytic leukemia), NB₄ (acute promyelocytic leukemia) and HL-60 (acute promyelocytic leukemia) were obtained from the Peking Union Medical College cell bank (Beijing, China). Cells were cultured in RPMI 1640 medium supplemented with 10% fetal calf serum (FCS), and maintained at 37°C in a humid atmosphere of 5% CO₂ in air. The cells were counted each day with a hemacytometer and then passaged every 2 days to maintain them in the exponential growth phase (i.e. maintained at 1-2×10⁵ cells/ml). To evaluate cell viability, cells were mixed with equal volumes of 0.4% trypan blue solution, and then immediately examined under the microscope. All of the cell culture reagents were purchased from Sigma.

Isolation of leukemic blasts

Normal peripheral lymphocytes and leukemic bone marrow cells were obtained from 3 volunteer donors and 21 patients treated at the Hematology Unit of First Clinical Medical College of Harbin Medical University for newly diagnosed AML before chemotherapy. According to the French-American-British committee classification, there are 3 cases M1, 5 cases M2, 4 cases M3, 5 cases M4 and 4 cases M5. Enriched populations of blast cells (more than 95%) were obtained by Ficoll-Hypaque (Pharmacia) density gradient centrifugation [20]. Peripheral

lymphocytes were cultured with IL-2 (200 U/ml, Yope Biotech Limited Company, Shanghai, China).

Annexin-V Fluorescein Isothiocyanate/Propidium Iodide (FITC/PI) Double Staining Assay

Annexin V-FITC apoptosis detection kit (BD Pharmingen, San Diego, CA) was used to distinguish and quantitatively determine the percentage of dead, viable, apoptotic and necrotic cells after treatment with drugs according to the manufacturer's instructions. The cells were seeded at 4×10⁵ cells/ml in 6-well plates. After treatment with drugs, the cells were harvested, washed twice with ice-cold phosphate-buffered saline (PBS) and resuspended in 100 µl of binding buffer. A total of 5 µl of Annexin V-FITC and 10 µl of PI were added and the mixture was incubated in the dark for 30 min. Then, 400 µl of binding buffer was added to the cells. The labeled cells (10,000/sample) were analyzed by measuring fluorescence intensity using FACS can flow cytometer (BD Bioscience) in conjunction with CellQuest software (BD Biosciences, San Jose, CA).

Measurement of nuclear fragmentation

Apoptotic death was evaluated by nuclear fragmentation in 46'-diamidino-2-phenylindole-2 HCl (DAPI)-staining cells. After fixation in 70% ethanol for 10 min, cells were stained with DAPI (0.5 µg/ml) for 10 min, and observed under UV-light using a confocal microscope (R2100AG2, Bio-Rad, Melville, NY). Ten different fields were randomly selected for counting 300 cells. The percentage of cells with fragmented nuclei was then calculated.

Mitochondrial membrane potentials assay

JC-1 probe (Sigma, St Louis, MO, USA) was employed to measure mitochondrial depolarization. Briefly, cells were incubated with an equal volume of JC-1 staining solution (5 µg/ml) at 37 °C for 20 min and rinsed twice with PBS. Mitochondrial membrane potential ($\Delta\Psi_m$) was determined using FACScan flow cytometer (BD Bioscience), and the mean fluorescence intensities were calculated and employed to express $\Delta\Psi_m$ alteration.

Patch-clamp recording of Kv current

Cells were transferred to the recording chamber, which was attached on the stage of an inverted phase-contrast microscope (IX71, Olympus, Tokyo, Japan). To immobilize the cells, they were adhered to the chamber with a bottom glass coated with poly-L-lysine (Sigma, St Louis, MO, USA). Cells were bathed at room temperature (20-25°C) and then superfused by gravity at a rate of about 2-4ml/min (bath volume 2ml) with an extracellular solution containing (in mM) (Sigma, St Louis, MO, USA) 136.5 NaCl, 5.4 KCl, 1.8 CaCl₂, 0.53 MgCl₂, 5.5 glucose and 5 HEPES-NaCl buffer, pH 7.4. The patch pipettes were made from Kimax capillary tubes (Kimble Glass, Vineland, NJ) using a vertical two-step electrode puller (PB-7, Narishige, Tokyo, Japan) and the tips were fire-polished with a microforge (MF-83, Narishige, Tokyo, Japan). The pipette solution contained (in mM) (Sigma, St Louis, MO, USA) 135 K-aspartic acid, 2 MgCl₂, 1.1 EGTA, 0.1 CaCl₂ and 10 HEPES-KOH buffer, pH 7.2. The resistance of the patch pipette was 3-5 MΩ when it was

immersed in extracellular solution. When the seal resistance exceeded 4GΩ, the whole cell membrane currents were recorded. Whole-cell voltage-clamp recordings were performed to record the voltage-gated potassium currents in NB₄, HL-60 and THP-1 cells using Axopatch 700B patch-clamp magnifying instrument (Axon Instruments, Foster City, CA, USA). For the voltage-gated potassium currents recording, the membrane voltage was stepped to -90mV for 1s followed by a ramp to +60 mV from a holding potential of -80 mV. All the records were stored on hard disk for the post-experiment analysis.

Transmission electron microscopy

NB₄, HL-60, and THP-1 cells were cultured in Petri dishes with 4mM 4-AP for 72h. 5×10^6 cells were collected by centrifugation at 12 000 g for 5 min and washed twice with PBS. The pelleted cells were fixed in 2.5% cold glutaraldehyde supplemented with 0.1 M of sodium cacodylate/ 1% sucrose buffer for 24 h. The cells were washed three times with PBS, then postfixed in 1% osmium tetroxide (60 min), encapsulated in 1% agar, stained with uranyl acetate and phosphotungstic acid, and dehydrated in a series of graded ethanolic solutions. Propylene oxide was added before the cells were finally embedded in Epon 812-Araldite mixture. Ultrathin sections (50 nm) were cut using LKL-208 ultramicrotome, placed under 200 mesh standard copper grids and examined under JEM-1220 transmission electron microscope.

Measurement of Intracellular Ca^{2+} Concentration [Ca^{2+}]_i

Cells were loaded with Fluo-3/AM (5μmol/L). Fluorescent intensity of Fluo-3/AM-loaded cells were detected using laser scanning confocal microscope (Olympus FV-300) with 488 nm for excitation from an argon ion laser and 530 nm for emission. Acquisition rate was 1 frame per 20 s and [Ca^{2+}]_i was monitored for at least 600 s. Drugs were added between the 1st and 2nd scan. The fluorescent intensities before (FI₀) and after (FI) drug administration were recorded. Quantitative changes in [Ca^{2+}]_i were inferred from the ratio of FI/ FI₀.

Reverse transcriptase-PCR (RT-PCR)

Total RNA was extracted with TRIzol (BRL Life and Technologies, MD). The cDNAs were amplified from 2 μg of total RNA using ThermoScript RT-PCR System (Invitrogen, Carlsbad, CA). The following primer pairs were used for RT-PCR: P₂X₇, 5'-TCT GCAAGATGT CAA GGG C-3', 5'-TCA CTC TTC GGA AAC TCT TTC C-3'; β-actin, 5'-AGC GGG AAA TCG TGC GTG-3', 5'-CAG GGT ACATGG TGG TGC C-3'.

Assessment of Caspase Activity

ApoAlert® caspase fluorescent and colorimetric assays (BD Biosciences Clontech, CA, U.S.A.) were used to determine the enzyme activity of caspase-3, -8 and -9. After incubation with 4mM 4-AP for 3.5, 7 and 14h, cells were collected and lysed in ice-cold buffer. The homogenate was centrifuged at 12000g for 10 min at 4 °C. Caspase activities in the supernatant were determined by cleavage of the specific chromophore-conjugated substrates. The substrate peptides of caspase-3, -8 and -9 were conjugated to 7-amino-4-trifluoromethyl coumarin (AFC), p-nitroaniline (p-NA) and 7-amino-4-methyl coumarin

(AMC), respectively. Caspase-3, -8 and -9 were measured quantitatively by comparing fluorescent intensity on a fluorescence spectrophotometer (Hitachi F-2500, Japan). Caspase-3, -8 and -9 activity was determined by absorbance of p-NA at 405 nm in a microplate reader (BIO-TEK ELX800, USA).

Small RNA interference of P₂X₇ receptor

P₂X₇ siRNA was designed using online program from Invitrogen, siDirector, and Wistar. These sequences were as the followings: P₂X₇ siRNA, 5'-CGA UGG ACU UCA CAG AUU U-3' and 5'-ACA UCC UGC CAG GUU UAA ATT-3'; control siRNA, 5'-CGA CAU ACU GUA CAG GCC UTT-3'. The duplex of each siRNA were synthesized by Sigma-Proligo. The siRNA (50 μM) was mixed with 100μl HiPerFectin and added into 8ml NB₄ cells (5×10^6 /ml) for 48 h in OPTI-MEM medium with 5% FCS. Cells were kept in culture for another 48h before collection for Western blotting, laser scanning confocal microscope and FITC/PI double staining assay.

Measurement of ATP concentration

NB₄ cells were treated with 4-AP (4mM) for 6h. After centrifugation, the supernatant was collected to detect extracellular ATP concentration by luciferin-based ENLITEN ATP Assay (Promega, Madison, USA) following the manufacturer's instructions.

Western blots

Cells were lysed by RIPA buffer (100 mM NaCl, 2 mM EDTA, 1 mM PMSF, 1% NP-40 and 50 mM Tris-HCl [pH 7.2]). Western blots were performed by a standard enhanced chemiluminescence (ECL) method (Amersham) using the following antibodies: GAPDH (Santa Cruz Biotechnology; Santa Cruz, CA); anti-P₂X₇ antibodies (BD Bioscience Pharmingen).

Reagents

Fluo-3/AM was purchased from Molecular Probes (Eugene, Ore, USA). 4-aminopyridine (4-AP), ethylene glycol bis(2-aminoethyl ether) tetraacetic acid (EGTA), Flufenamic acid (FA), verapamil (Ver), KN-62, 4',6'-diamidino-2-phenylindole (DAPI), thapsigargin (TG), charybdotoxin and all other chemicals were purchased from Sigma Diagnostics.

Statistical analysis

Data are presented as mean ± SEM. Comparisons between controls and treatments were analyzed by two-tailed analyses of variance (ANOVA) followed by Dunnett's test. Difference was considered significant when p < 0.05.

Results

Effects of 4-AP on the Growth of Human AML Cell Lines

We first measured the effects of 4-AP on continuously growing AML cell lines. The AML cell lines, NB₄, HL-60 and THP-1, were treated with incremental

doses up to 8 mM of 4-AP for 72 h. 4-AP suppressed cell viability in a dose-dependent manner in all cell lines (Fig 1A). The IC_{50} of 4-AP was 3.74mM (NB₄), 3.61 mM (HL-60) and 3.68 mM (THP-1), respectively.

As continuously growing cell lines exert different proliferative activity and survival requirements than do primary leukemic cells, their susceptibility to antileukemic compounds may be different as well [21]. We thus tested the effects of 4-AP on cell viability of primary cultured AML cells of 21 cases of M₁-M₅ patients. At the concentration of 8mM, 4-AP markedly reduced cell viability in all 21 cases of AML patients, and the median cell viability is 7% (ranging from 1% to 18%) of that measured in parallel untreated cultures (Fig 1B). The effects of 4-AP remained evident at 4mM (median cell viability is 48%) and 2 mM (median cell viability is 82%) (Fig 1B).

4-AP induces apoptosis in AML cells

Previous studies indicated that 4-AP inhibits cell proliferation, but does not cause cytotoxicity in ML-1 cells [19]. In this study, we found that 4-AP induced significant apoptosis in AML cells. NB₄, HL-60, and THP-1 cells treated with 4 mM 4-AP for 72h revealed typical nuclear features of apoptosis including the pycnosis of cell nucleus, and the appearance of apoptotic body with nuclear membrane observed using the electron microscopy (Fig 2A). We also employed Annexin V- FITC/PI and DAPI staining to explore the induction of apoptosis by 4-AP. Treatment with 4mM 4-AP significantly increased apoptotic cells (NB₄: $p < 0.001$ vs. control; HL-60: $p < 0.001$ vs. control; THP-1: $p < 0.001$ vs. control) (Fig 2B, C, D). We also observed the apoptosis of 21 primary cells samples of AML patients treated with 4mM 4-AP for 72 h by Annexin-V/PI staining, and 4-AP induced apoptosis in all the 21 cases (Fig 2E).

Effects of 4-AP on mitochondrial membrane potential ($\Delta\Psi_m$) and Caspase activity

The $\Delta\Psi_m$ disruption is critical for apoptosis. When NB₄, HL-60, and THP-1 cells were treated with 4-AP (4mM), the $\Delta\Psi_m$ disruption began to increase at 24 h and further increased in a time-dependent manner (Fig 3A), further indicating the induction of apoptosis.

Caspases play key roles for both commitment and execution of apoptosis [22]. Caspase-3 is one of the downstream effectors of the caspase family and is involved in both the mitochondrial apoptotic pathway and the death receptor pathway. Caspase-3 is synthesized through cleavage in response to apoptotic stimuli by

Fig. 1. Suppression of 4-AP on the growth of both AML cell lines (A) and primary cultured AML cells of patients (B). NL, normal peripheral lymphocytes. Cells were treated with 4-AP for 72h. Data in Fig. 1A are expressed as mean $\pm$ SEM. n=5 individual experiments. In Fig 1B, cell viability of 21 cases of M1-M5 patients was evaluated after 72 h's incubation with 4-AP at the indicated concentrations.

initiator caspases (including caspase-2, -8, -9, -10, -11 and -12) and then becomes activated [23]. As shown in Fig 3B, 4-AP enhanced the activation of caspase-3 in a time-dependent manner. Treatment with 4-AP (4mM) for 14h caused a 2.5 fold increase in caspase-3 activity ($P < 0.05$ vs control group). Moreover, 4-AP(4mM) treatment dramatically increased caspase-9 activity by 2.9 fold, while caspase-8 activity was not changed, illustrating the activation of caspase-3 and -9 but not caspase-8 in the apoptotic process of NB₄, HL-60 and THP-1 cells induced by 4-AP.

Effects of 4-AP on voltage-gated potassium currents in AML cells

A typical outward rectifier current was recorded by using patch-clamp technique in NB₄ cells (Fig 4A). The current recorded was activated rapidly and did not inactivate during 1000ms test pulses, and was blocked by 4mM 4-AP (Fig 4B). The current was not blocked by the specific inhibitor of Ca²⁺-activated K⁺ channels (K_{Ca}), 1 μ M charybdotoxin (Fig 4C). The electrophysiological features of outward rectifier currents appeared clearly similar to those reported in other tumor cell lines [12, 24]. The effect of 4-AP on the current-voltage relations in

Fig. 2. 4-AP induces apoptosis in AML cells. A. Apoptotic death of NB4, HL-60 and THP-1 cells treated with 4 mM 4-AP observed by using electron microscopy. B. Apoptotic death of NB4, HL-60 and THP-1 cells treated with 4-AP (4 mM) for 72 h detected by flow cytometry after Annexin V-FITC/PI double staining. In all panels, cells in the lower left quadrant are alive, cells in the lower right quadrant are in early apoptosis, cells in the upper right are in late apoptosis, and cells in the upper left quadrant are dead. C. Cellular morphology was photographed under a confocal microscope after the indicated treatments for 72h with DAPI staining. D. Statistical analysis of the apoptosis of NB4, HL-60 and THP-1 after 4-AP treatment. Data are expressed as mean $\pm$ SEM. n=5 individual experiments. * $p < 0.05$ vs control. E. Apoptosis in primary cell of 21 AML patient cases after 4-AP (4 mM) treatment for 72 h with Annexin V-FITC/PI double staining.

Fig. 3. Influence of 4-AP on MMP and caspases activity in AML cells. A. Disruption of $\Delta\Psi_m$ in NB4, HL-60 and THP-1 cells treated with 4-AP (4 mM) for 24, 48 and 72 h. $\Delta\Psi_m$ was evaluated with JC-1 probe and its intracellular mean fluorescence intensities (MFIs) were measured. B. Activity of caspase-3, 8 and 9 in NB4 cells treated with 4-AP (4mM) for 7 and 14h. Data are expressed as mean $\pm$ SEM. n=3. * $p < 0.05$ vs 0h.

the range of -90mV and $+60\text{mV}$ was demonstrated in the 3 different cell lines NB₄, HL-60, and THP-1 (Fig 4D, E, F). At $+60\text{ mV}$, 4-AP(4mM) reduced the peak amplitudes of K_v current by 47.5 % (NB₄), 48.2% (HL-60) and 42.2% (THP-1) of their respective controls (Fig 4D, E, F).

Effects of 4-AP on intracellular Ca^{2+} concentration

Mobilization and concentration of intracellular calcium are an essential and well-established step in cell proliferation, activation and apoptosis [22]. To determine

Fig. 4. 4-AP inhibited voltage-gated potassium currents (Kv) in NB4 cells. A-C, representative traces of Kv. Normal, 4-AP treatment, and charybdotoxin treatment. D-F. Effect of 4-AP on I-V relationship of Kv current in NB4, HL-60 and THP-1 cells. Data are expressed as mean $\pm$ SEM. n=14.

whether 4-AP affected intracellular Ca^{2+} signaling in the leukemic cell lines, we measured the changes in cytosolic Ca^{2+} concentration. Exposure to 4 mM 4-AP caused a rapid and sustained rise in intracellular Ca^{2+} concentration of NB₄ cells (Fig 5A). In nominal Ca^{2+} -free medium containing 1 mM EGTA (Fig 5B,G), a chelator of extracellular calcium, 4-AP induced $[\text{Ca}^{2+}]_i$ increment was inhibited. While verapamil (100 $\mu\text{mol/L}$) in normal Ca^{2+} -containing medium (Fig 5C,G), a voltage-operated Ca^{2+} channel blocker produced no effect on 4-AP induced $[\text{Ca}^{2+}]_i$ increment. Flufenamic acid (200 $\mu\text{mol/L}$), a nonselective cation channel blocker, completely blocked 4-AP induced Ca^{2+} influx (Fig 5D,G). These results illustrate that 4-AP induced Ca^{2+} influx through the activation of NSCCs, a finding that is consistent with previous reports [21]. Furthermore, the presence of ionotropic P_2X_7 receptors, belonging to nonselective cation channel, has been found in AML cells [25]. We found that KN-62 (1 $\mu\text{mol/L}$), a specific blocker of P_2X_7 receptors, completely blocked 4-AP induced Ca^{2+} influx, suggesting that 4-AP induced Ca^{2+} influx was through the activation of the P_2X_7 receptor (Fig 5E,G). 4-AP can increase intracellular calcium when the intracellular calcium stores were emptied using TG (1 μM), a specific

inhibitor of sarcoplasmic-endoplasmic reticulum Ca^{2+} -ATPase (SERCA) (Fig 5F, G). Furthermore, we found that treatment with KN-62 (1 $\mu\text{mol/L}$) significantly suppressed 4-AP-induced apoptosis in NB₄, HL-60 and THP-1 cells (Fig 5H), indicating that P_2X_7 receptor are involved in the pro-apoptotic action of 4-AP. P_2X_7 receptor mRNA levels were detected in NB₄, HL-60 and THP-1 cells as shown in Fig 5I.

Effect of P_2X_7 knockdown on the response of NB₄ to 4-AP and Release of ATP induced by 4-AP

To further confirm the involvement of P_2X_7 receptor in the pro-apoptotic effect of 4-AP in AML cells, we employed siRNA technique to knockdown P_2X_7 receptor. The siRNA used in this study suppressed the expression of P_2X_7 receptor, with the protein expression decreased by about 78% after adding siRNA- P_2X_7 (Fig 6A). The increment of $[\text{Ca}^{2+}]_i$ evoked by 4-AP (4mM) was inhibited by si- P_2X_7 and si-random produced no effect (Fig 6B). Furthermore, suppressing P_2X_7 expression also abrogated 4-AP induced apoptosis of NB₄ cells (Fig 6C). These results indicated that P_2X_7 receptor plays a crucial role in the effect of 4-AP on AML cells. Moreover, 4-AP (4mM) treatment increased ATP release from NB₄ cells (Fig 6D).

Fig. 5. 4-AP induced extracellular calcium influx via P_2X_7 receptor mediated cation channels. A. Representative pictures of 4-AP induced intracellular calcium increment obtained in NB4 cells by using Laser scanning confocal microscope and 4-AP induced time-concentration trace of intracellular calcium. B-F. Representative traces of intracellular Ca^{2+} measurements under various conditions, including nominal Ca^{2+} -free medium containing 1 mM EGTA, including normal Ca^{2+} -containing medium containing Ver (100 μ M), FA (200 μ M), KN-62 (1 μ M) and TG(1 μ M). G. Statistical analysis of nominal Ca^{2+} -free medium containing 1 mM EGTA, normal Ca^{2+} -containing medium containing Ver (100 μ M), FA (200 μ M), KN-62 (1 μ M) and TG(1 μ M) on 4-AP induced intracellular calcium increment. H. Effect of KN-62 (1 μ M) on apoptosis of NB4, HL-60 and THP-1 cells induced by 4-AP (4mM). I. mRNA expression of P_2X_7 receptors. Data are expressed as mean $\pm$ SEM. * $p < 0.05$ vs control, # $p < 0.05$ vs 4-AP, $n = 5$.

Discussion

4-AP, a specific inhibitor of Kv channels, was shown to induce apoptosis in HepG₂ hepatoma cells [15]. In this study we found 4-AP induced apoptosis of AML cells (NB₄, HL-60 and THP-1). Depolarization of the mitochondrial membrane potential and release of

apoptotic proteins are the characteristic changes during cell apoptosis. We observed that 4-AP treatment resulted in disruption of $\Delta\Psi_m$. Disruption of $\Delta\Psi_m$ undergoes a series of changes during apoptotic death of cells, and loss of MMP together with the open of permeability transition pore induces the cytosolic release of cytochrome c and activation of initiator caspases-9, which activates the

Fig. 6. Effect of P_2X_7 knockdown on the response of NB4 to 4-AP and release of ATP induced by 4-AP. A. siRNA blocking efficiency on P_2X_7 in NB4 cells was confirmed by Western blot. Data are expressed as mean $\pm$ SEM. ** $p<0.05$ vs control, $n=4$. B. Effects of 4-AP on intracellular Ca^{2+} concentration in NB4 cells after knocking down P_2X_7 . Data are expressed as mean $\pm$ SEM. ** $p<0.05$ vs control, ## $p<0.05$ vs 4-AP. $n=5$. C. Knockdown of P_2X_7 blocked 4-AP induced apoptosis in NB4 cells Annexin V-FITC/PI staining. Data are expressed as mean $\pm$ SEM. ** $p<0.05$ vs control, ## $p<0.05$ vs 4-AP. $n=5$. D. 4-AP induced ATP release from NB4 cells. Data are expressed as mean $\pm$ SEM. ** $p<0.05$ vs control. $n=5$.

apoptosis executioner protease, caspase-3 through proteolytic cleavage at specific internal aspartate residues [26]. In this study caspase-9 and 3 activity increased dramatically after treatment with 4-AP while the activity of caspase-8 did not change. In this study the concentrations required for proapoptotic effect of 4-AP are less than those that induce toxic effects in normal lymphocytes. 4-AP also caused significant apoptosis of primary cultured AML cells of clinical patients, which indicates the potential of 4-AP in treating acute myelocytic leukemia. These results are consistent with Xu B et al's study, just that we found 4-AP caused apoptosis, while they showed that 4-AP inhibited proliferation of human myeloblastic ML-1 cell line [19].

In cancer cells, K^+ channels play crucial roles in cancer cell development, proliferation and migration [27] and are an excellent target for diagnosis and therapy [27]. Many agents inhibiting K^+ channels have been shown to suppress cell proliferation, including leukemic cells [28-30]. In this study we found NB₄, HL-60 and THP-1 cells all express functional K_v currents, which can be inhibited by 4-AP, indicating that 4-AP might exert its proapoptotic action via inhibition of potassium channels. However, as the resting potential of the cell lines is around -40 mV, and 4-AP inhibited K_v current at +40mV and +50mV,

implying that at the resting state inhibition of potassium channel may not contribute to its pro-apoptotic action on tumor cells at least at the resting state. As the resting potential of tumor cells are not constant in the phases of proliferation, and a transient hyperpolarization is required for the progression of the early G1 phase of the cell cycle [31]. Under this situation, it would be reasonable for 4-AP to take action by inhibiting potassium channel.

4-AP was shown to affect calcium mobilization [13-15]. Guse et al. demonstrated that 4-AP caused a transient increase of intracellular calcium [14]. 4-AP has been shown to block K^+ channels at the concentration used in this study, and thus depolarize membrane potential in many cell types [32-34], which caused calcium influx. As calcium overload has been shown to act as a common mediator of cell death [16] and a signal transducer of apoptosis [17], the proapoptotic action of 4-AP on AML cells may be due to its effect on $[Ca^{2+}]_i$. In this study, we found 4-AP induced a rapid and sustained increase of intracellular Ca^{2+} in AML cells, which is consistent with those previously described in other cell types [15]. We further explored the mechanism by which 4-AP increased intracellular Ca^{2+} , and found that deprivation of extracellular calcium using EGTA diminished $[Ca^{2+}]_i$ increase, suggesting that extracellular influx plays a major

role in this process. As in AML cells extracellular calcium mainly influx via voltage-dependent calcium channel and nonselective cation channel, we explored which of them accounts for 4-AP induced calcium influx. The fact that FA (a nonselective cation channel blocker) but not verapamil blocked 4-AP induced $[Ca^{2+}]_i$ increase means that nonselective cation channel is responsible for the influx of extracellular calcium. Furthermore, we identified mRNA expression of P_2X_7 receptor in NB₄, HL-60 and THP-1 cells, which is an ATP-gated cation channel expressed in hemopoietic cells and participates in both cell proliferation and apoptosis [35]. Interestingly, inhibition of P_2X_7 activity and knock down of P_2X_7 receptor expression abrogated 4-AP induced calcium influx and apoptosis, which strongly support the involvement of P_2X_7 receptor in this process. Consistently, Kim et al. showed that 4-AP induced apoptosis of HepG₂ human hepatoblastoma cells by activating Ca^{2+} influx through NSCCs by changing membrane potential. However, Dong et al. demonstrated that blocking of Kv currents by 4-AP induced apoptosis in HepG₂ cells, but not GH3 cells [36]. Wu et al. found that 4-AP directly stimulates high voltage-activated calcium channels in acutely dissociated neurons [37]. These studies indicated that blocking of Kv current may not always be the cause of cell apoptosis, and 4-AP can target on calcium channels directly. Therefore, when interpreting our data, we can not rule out the possibility that 4-AP induced apoptosis may be caused by the direct activation of mediated calcium influx, which requires

further study to clarify it.

Taken together, we found 4-AP induced apoptosis in both AML cell lines and primary cultured AML cells of patients. Inhibiting of Kv channel and the subsequent calcium influx mediated P_2X_7 receptors account for 4-AP's anticancer activity against AML cells. This study indicated that 4-AP represents a promising candidate for the development of novel agents for treating AML.

Abbreviations

4-AP (4-aminopyridine); AML (Acute myeloid leukemia); EGTA (Ethylene glycol bis(2-aminoethyl ether)tetraacetic acid); FA (Flufenamic acid); Ver (Verapamil); P_2X_7 (Purinergic receptor P_2X , ligand-gated ion channel, 7); MMP (Mitochondrial membrane potentials).

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