RESEARCH ARTICLE

Aberrant DNA Methylation and Epigenetic Inactivation of hMSH2 Decrease Overall Survival of Acute Lymphoblastic Leukemia Patients via Modulating Cell Cycle and Apoptosis

Cai-Xia Wang¹, Xiang Wang², Hai-Bai Liu², Zhi-Heng Zhou²*  

Abstract

Objective: Altered regulation of many transcription factors has been shown to play important roles in the development of leukemia. hMSH2 can modulate the activity of some important transcription factors and is known to be a regulator of hematopoietic differentiation. Herein, we investigated epigenetic regulation of hMSH2 and its influence on cell growth and overall survival of acute lymphoblastic leukemia (ALL) patients. Methods: hMSH2 promoter methylation status was assessed by COBRA and pyrosequencing in 60 ALL patients and 30 healthy volunteers. mRNA and protein expression levels of hMSH2, PCNA, CyclinD1, Bcl-2 and Bax were determined by real time PCR and Western blotting, respectively. The influence of hMSH2 on cell proliferation and survival was assessed in transient and stable expression systems. Results: mRNA and protein expression of hMSH2 and Bcl-2 was decreased, and that of PCNA, CyclinD1 and Bax was increased in ALL patients as compared to healthy volunteers (P<0.05). hMSH2 was inactivated in ALL patients through promoter hypermethylation. Furthermore, hMSH2 hypermethylation was found in relapsed ALL patients (85.7% of all cases). The median survival of patients with hMSH2 methylation was shorter than that of patients without hMSH2 methylation (log-rank test, P=0.0035). Over-expression of hMSH2 in cell lines resulted in a significant reduction in growth and induction of apoptosis. Conclusions: This study suggests that aberrant DNA methylation and epigenetic inactivation of hMSH2 play an important role in the development of ALL through altering cell growth and survival.

Keywords: Acute lymphoblastic leukemia - hMSH2 - DNA methylation - survival - cell apoptosis

Asian Pac J Cancer Prev, 15 (1), 355-362

Introduction

Acute lymphoblastic leukemia (ALL) is the most common type of leukemia in childhood and adults. While the survival rate of ALL patients has been improved obviously, nearly one quarter of children with ALL will die (Gaynon, 2005). ALL in adults affects a comparatively young population and has proved to be refractory, with the 5-year survival rate of around 40% (Plasschaert et al., 2004). ALL originates from malignant transformation of lymphocyte progenitor cells into leukemic cells of the B-cell and T-cell lineages (Pui et al., 2011). However, one of the known genetic aberrations in ALL is insufficient to induce this disease (Pui et al., 2004), suggesting that there are other genetic or epigenetic alterations in the leukemic transformation.

Mismatch repair (MMR) system is involved in the DNA damage recognition and repair. Human mutS homolog 2 (hMSH2) functions as a core MMR protein and usually forms hetero-dimers with protein homologs hMSH3 or hMSH6 (Fishel, 2001). The hetero-dimer is fundamental for the DNA damage recognition and crucial for the stability of MMR protein homologs (Marsischky et al., 1996). Defects in MMR proteins have been found to be associated with reduced or absent benefit from 5-FU adjuvant chemotherapy in clinical trials (Ribic et al., 2003). MMR impairment appears to cause reduced incorporation of 5-FU metabolites into DNA, leading to reduced G2/M arrest and apoptosis after 5-FU treatment (Meyers et al., 2005; Hewish et al., 2010). The deficiencies of MMR genes are also associated with MNG, 6-thioguanine and cisplatin (Fiumicino et al., 2000; Meyers et al., 2001; Loo et al., 2005). Altered expression of key regulatory transcription factors has been shown to play a critical role in the leukemia development (O’Neil and Look, 2007). Molecular biological studies have shown that hMSH2 may be functionally relevant in the lymphoid cells and potentially ALL.

It is now clear that epigenetic alterations are as important as genetic changes in the development of cancer (Costello and Plass, 2001). Many well established tumor suppressor genes have been shown to be inactivated predominantly

¹Department of Internal Medicine, Guangzhou First People’s Hospital, Guangzhou Medical University, ²School of Public Health, Guangzhou Medical University, Guangzhou, China *For correspondence: zhouziheng_00@163.com
by promoter hypermethylation and many of them linked to leukemia development act as epigenetic regulators (Slany, 2005). hMSH2 has been found to be implicated in the DNA mismatch repair system. Inactivation of this gene due to promoter hypermethylation has been reported to be associated with some human cancers (Deguchi et al., 2003). It is reported that hMSH2 expression correlates with allelic imbalance on the chromosome 3p in the non-small cell lung cancer (Xinarianos et al., 2000). This study aimed to investigate the epigenetic regulation of hMSH2 on the cell growth and survival. Our results showed that hMSH2 was inactivated by promoter hypermethylation in most of ALL. Over-expression of hMSH2 in ALL cell lines resulted in dramatic reduction in cell growth and induced apoptosis. Overall, our findings suggest that the epigenetic inactivation of hMSH2 plays an important role in the occurrence of ALL, probably through altering cell growth and survival.

Materials and Methods

**Patients and clinical information**

Bone marrow or peripheral blood samples were collected from 60 ALL adults who were included in the present study including 32 males and 28 females, with a median age of 32.4 years. All the 60 samples were taken at initial diagnosis and 14 samples at relapse. Clinical information was collected from each patient by medical record reviewing. All patients received treatment in our hospital from 2005 to 2011. The clinical characteristics of these patients are listed in Table 1. Findings in follow up were retrieved from Department of Internal Medicine, Guangzhou First People’s Hospital, Guangzhou Medical University, and the last follow-up was done in October 2012. The median follow-up duration for survived patients was 41.4 months (range, 11-60 months). Bone marrow or peripheral blood was also collected from thirty healthy volunteers as controls.

All the patients were diagnosed by pathological examination of bone marrow. Results showed very high white cell counts and >95% BCR/ABL positive cells. For patients with blast crisis, peripheral blood was obtained, and leucocytes were directly separated. Assay showed 80-99% blasts.

Blood was collected into heparinized tubes before treatment and processed for assay within 24-36 h. Leukemic cells were isolated by 1.077 g/mL Ficoll-Isoopaque (Pharmacia) density gradient centrifugation. The proportion of leukemic cells was estimated under a light microscope following May–Grünwald-Giemsa staining. The samples used for analysis contained at least 90% lymphoblasts after separation. Pellets of 2-10 million cells were immediately frozen and stored at -70 °C.

**Ethical approval**

This study was in line with generally accepted ethical principles and approved by the Research Ethnic Committee of Affiliated Guangzhou First People’s Hospital of Guangzhou Medical University. All the procedures were performed in accordance with the principals of the Declaration of Helsinki. Written informed consent was obtained from all the patients before study.

**DNA extraction and bisulfite modification**

DNA was extracted from paraffin-embedded bone marrow. Samples were deparaffinized using xylene and ethanol, followed by digestion with proteinase K. After conventional DNA extraction, DNA was modified with sodium bisulfite. The bisulfite treatment of DNA may convert the unmethylated CpG to UpG without methylation. In brief, DNA was denatured in 0.2 N NaOH at 37°C for 10 min and incubated with 3 M sodium bisulfite at 50°C for 16 h. DNA was then purified using the Wizard cleaning system (Promega, Madison, WI) and desulfonated with 0.3 N NaOH at 25°C for 5 min. DNA was then precipitated with ammonium acetate and ethanol, washed with 70% ethanol, dried, and re-suspended in H2O.

**Detection of mRNA expression of hMSH2, PCNA, CyclinD1, Bcl-2 and Bax**

Total RNA was isolated using the TRIzol reagent. Reverse transcription was performed using a TITANIUM real-time PCR (RT-PCR) kit (Clontech, Mountain View, CA) according to the manufacturer’s instructions. The mRNA expression was quantified using a fluorescence-based RT-PCR according to manufacturer’s instructions (Bio-Rad Laboratories). The primers used for RT-PCR of hMSH2, PCNA, CyclinD1, Bcl-2 and Bax are shown in Table 2.

**Western blot assay**

At the pre-designed time points, cells were washed twice with 5 ml of ice-cold CMF-PBS followed by addition of 0.5 ml of lysis buffer containing additional phosphatase (cocktails I and II) and protease inhibitor (Calbiochem). Cells were harvested, treated with lysis

---

**Table 1. Characteristics of ALL Samples**

<table>
<thead>
<tr>
<th>BCP ALL</th>
<th>T-ALL</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of patients (%)</td>
<td>39 (65.0)</td>
<td>21 (35.0)</td>
</tr>
<tr>
<td>Median age (yr)</td>
<td>32.2</td>
<td>32.5</td>
</tr>
<tr>
<td>Sex ratio (M:F)</td>
<td>21:18</td>
<td>11:10</td>
</tr>
<tr>
<td>Median WBC (109/L)</td>
<td>42.7</td>
<td>28.3</td>
</tr>
<tr>
<td>(12:21)-positive (%)</td>
<td>16 (41.0)</td>
<td>0 (0.0)</td>
</tr>
<tr>
<td>Diagnostic (%)</td>
<td>29 (74.4)</td>
<td>17 (80.9)</td>
</tr>
<tr>
<td>Relapsed ALL, (%)</td>
<td>10 (25.6)</td>
<td>4 (19.4)</td>
</tr>
<tr>
<td>Median follow-up (range)</td>
<td>41(11-60)</td>
<td>42(12-60)</td>
</tr>
</tbody>
</table>

**Table 2. Primers and Amplicon Sizes for Selected Human Genes with Quantitative Real-time PCR**

<table>
<thead>
<tr>
<th>Genes</th>
<th>Primers</th>
<th>Size (bp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>hMSH2</td>
<td>Forward: 5'-AAAGCCAGGAGATGCAAATTG-3'</td>
<td>126</td>
</tr>
<tr>
<td>Reverse: 5'-CTCGGCAATCCAGGGGATTC-3'</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PCNA</td>
<td>Forward: 5'-GCCCTCAAAGACCTCATCAA-3'</td>
<td>338</td>
</tr>
<tr>
<td>Reverse: 5'-TTCGGGATTCCAAGTTGCTC-3'</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CyclinD1</td>
<td>Forward: 5'-GCCACAGCTGACTCCAGAAG-3'</td>
<td>328</td>
</tr>
<tr>
<td>Reverse: 5'-TTCCCGAATTTGTTTGGGCGAGGCCGCCGAGGAT-3'</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bcl2</td>
<td>Forward: 5'-ATGGGAGTGAACTGCTTGGAGTG-3'</td>
<td></td>
</tr>
<tr>
<td>Reverse: 5'-TCCCGAATTTGTTTGGGCGAGGCCGCCGAGGAT-3'</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bax</td>
<td>Forward: 5'-GGGGTGGGCTTCCTTTCTACT-3'</td>
<td>110</td>
</tr>
<tr>
<td>Reverse: 5'-CCCGAGGAGGTCCAGGTTCGC-3'</td>
<td></td>
<td></td>
</tr>
<tr>
<td>β-actin</td>
<td>Forward: 5'-ACACTGGGCTCACCTACAGAGG-3'</td>
<td>250</td>
</tr>
<tr>
<td>Reverse: 5'-AGGGGCGGGACTGCTACATCT-3'</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Aberrant DNA Methylation and Epigenetic Inactivation of hMSH2 Decrease Overall Survival of ALL Patients

Cell lines and transfections
The human ALL cell lines used in this study were Nalm-6 cells (B-cell precursor, ALL) which were kindly provided by the American Type Culture Collection and Reh cells which were obtained from DSMZ (Braunschweig, Germany). Both cell lines have been previously characterized as B-precursor ALL cells. The early B-lymphoid antigen CD19 is expressed on >95% of cells.

ALL cell lines were maintained in RPMI containing 2 mM glutamine and 10% fetal calf serum (FBS) in an environment with 95% O2/5% CO2, at 37°C. For hMSH2 over-expression study, Nalm6 cells were treated with 1 μM 2′-deoxy-5-azacytidine (Sigma) for 24 h and then collected for qRT-PCR five days later. For transfection, the hMSH2 cDNA was cloned into the pIRE5-eGFP vector to produce the pIRE5-hMSH2-eGFP vector. This allows the expression of hMSH2 and eGFP in a single transcript, but two proteins are translated separately due to the presence of IRES sequence between hMSH2 and eGFP. Transfections were carried out using the Nucleofector system (Amaxa, Koeln, Germany) according to the manufacturer’s instructions using 5x106 cells and 2 μg of DNA. Cells were transfected with either pIRE5-eGFP or pIRE5-hMSH2-eGFP. Transfected cells were either used for transient transfections or treated with 800 μg/ml G418 following transfection to select the stably transfected cells. The G418 resistant cells were collected, and the GFP positive cells were determined by flow cytometry. Then, the GFP positive cells were sorted using a FACSA cell sorter (BD Biosciences, Oxford, UK), to acquire a cell population containing transfectants at a high level. hMSH2 expression in this population was confirmed by qRT-PCR. These bulk cultures, as opposed to single clones, were used for subsequent experiments to avoid any potential influence of site of integration on downstream analysis.

Growth assays
The effect of hMSH2 on the growth of ALL cells was assessed using the GFP positive Nalm6 cells and Reh cells. Stably transfected cells were grown for approximately 7 days, and the GFP expression was determined. Only the cells with high GFP positivity (>80% for Nalm6 and 70-80% for Reh) were used for further assays. Cells were counted using the Vi-CELL System (Beckman Coulter, High Wycombe, UK), and then 20,000 viable cells without transfection, transfected with blank vector and transfected with hMSH2 vector were seeded in triplicate in 12-well plates. Samples were harvested at 4 and 7 days and counted using the Vi-CELL system. Data shown were the averages from 4 independent experiments.

Growth assays were also carried out following dexamethasone treatment. Following cell counting with the Vi-CELL system, 30,000 transfected Nalm6 cells (either blank vector or hMSH2 vector) were plated in triplicate in 12-well plates. These cells were treated with 0, 1 and 5 mM dexamethasone. Cells were harvested at 4 and 7 days for counting using the Vi-CELL system. Data shown were averages from 3 independent experiments.

Detection of apoptosis
Apoptotic cells were measured by flow cytometry using the Annexin V kit (BD Biosciences, Oxford, UK) according to the manufacturer’s instructions. Data shown were the averages from 4 independent experiments.
Combined bisulfite restriction analysis (COBRA)

<table>
<thead>
<tr>
<th>Locus</th>
<th>Primer Sequence</th>
<th>Annealing temp (restriction enzyme)</th>
<th>Product Size (of PCR cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>hMSH2 (-73bp)</td>
<td>F:5’GGGAAGTTGGTYGGTGTGTG3’ R:5’CRACCCCCACCCCAACTTATTT3’</td>
<td>156 (TaqI)</td>
<td>55 (7), 53 (38)</td>
</tr>
<tr>
<td>hMSH2 (+91bp)</td>
<td>F:5’GAGGYYGGAAATGTTAGTG3’ R:5’ACTTCTCCRACATACCTAAAA3’</td>
<td>158 (HpyCH4IV)</td>
<td>55 (7), 53 (38)</td>
</tr>
</tbody>
</table>

Bisulfite Sequencing of MSH2

<table>
<thead>
<tr>
<th>Locus</th>
<th>Primer Sequence</th>
<th>Annealing temp (restriction enzyme)</th>
<th>Product Size (of PCR cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>F:5’GGGAAGTTGGTYGGTGTGTG3’ R:5’CRACCCCACCCCAACTTATTT3’</td>
<td>191</td>
<td>55(7), 53 (30)</td>
</tr>
<tr>
<td>2nd</td>
<td>F:5’GGGAAGTTGGTYGGTGTGTG3’ R:5’CRACCCCACCCCAACTTATTT3’</td>
<td>191</td>
<td>55 (35)</td>
</tr>
</tbody>
</table>

Results

Expression of hMSH2, PCNA, CyclinD1, Bcl-2 and Bax in ALL

To investigate the effect of ALL on the expression of hMSH2, PCNA, CyclinD1, Bcl-2 and Bax, the mRNA and protein expression of these genes were determined by qPCR and western blot assay, respectively. Both the mRNA and protein expression of hMSH2 and Bcl-2 reduced in mononuclear cells of ALL patients, while that of PCNA, CyclinD1 and Bax increased in these cells. Furthermore, the expression of these genes in ALL patients was significantly different from that in healthy volunteers (P<0.05) (Figure 1A, B). These suggested that there were aberrant mRNA and protein expression of genes related to DNA repair, cell cycle, and cell apoptosis in ALL.

hMSH2 as a target for epigenetic inactivation in ALL

To determine the potential role of hMSH2 promoter hypermethylation in the leukemia, the methylation status of genes was quantitatively analyzed in ALL by COBRA assay. No methylation was detectable in normal peripheral blood, but hMSH2 hypermethylation (>50% methylated DNA) was identified in the peripheral blood of most ALL patients. This was true for ALL (70% of cases exhibiting >50% methylation, Table 3). To further analyze the methylation status of hMSH2, a second quantitative methylation assay, pyrosequencing, was used to confirm the methylation level in a subset of ALL samples. Pyrosequencing demonstrated that hMSH2 hypermethylation (>50%) were frequently observed in ALL samples, as shown in the COBRA analysis. Furthermore, samples with methylation identified by COBRA assay were consistent with those with methylation identified by pyrosequencing assay.

The hMSH2 hypermethylation was detected in patients and healthy volunteers. Additional 6 ETV6- RUNX1

Statistical analysis

Statistical analysis was done with SPSS version 13.0 software (SPSS Inc., Chicago, IL, USA). Data were expressed as mean ± standard deviation. Differences between groups were analyzed with t-test or analysis of variance. Cell count was expressed as rates and the differences were compared with chi-square test. The survival of hMSH2 methylated cells and unmethylated cells in ALL patients were expressed as median and comparisons were carried out using the Kaplan-Meier method (Log-rank). A value of P <0.05 was considered statistically different.
Aberrant DNA Methylation and Epigenetic Inactivation of hMSH2 Decrease Overall Survival of ALL Patients

Table 4. Frequency of hMSH2 Hypermethylation in Leukemia

<table>
<thead>
<tr>
<th>Items</th>
<th>Total</th>
<th>Methylated, N (%)</th>
<th>Unmethylated, N (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median age (yr)</td>
<td>32.4</td>
<td>31.2</td>
<td>33.3</td>
</tr>
<tr>
<td>Sex ratio</td>
<td>32:28:00</td>
<td>22:20</td>
<td>10:08</td>
</tr>
<tr>
<td>Median WBC (×10^9/L)</td>
<td>42.7</td>
<td>50.5</td>
<td>37.8</td>
</tr>
<tr>
<td>BCP-ALL (%)</td>
<td>39</td>
<td>24 (61.5)</td>
<td>15 (38.5)</td>
</tr>
<tr>
<td>T-ALL (%)</td>
<td>12</td>
<td>7 (58.3)</td>
<td>5 (41.7)</td>
</tr>
<tr>
<td>Diagnostic (%)</td>
<td>46</td>
<td>33 (71.7)</td>
<td>13 (28.3)</td>
</tr>
<tr>
<td>Relapsed ALL* (%)</td>
<td>14</td>
<td>12 (85.7)</td>
<td>2 (14.3)</td>
</tr>
<tr>
<td>t(12;21)-positive (%)</td>
<td>16</td>
<td>12 (75.0)</td>
<td>4 (25.0)</td>
</tr>
<tr>
<td>t(12;21)-negative (%)</td>
<td>40</td>
<td>17 (42.5)</td>
<td>32 (57.5)</td>
</tr>
<tr>
<td>HeH (%)</td>
<td>15</td>
<td>5 (33.3)</td>
<td>10 (66.7)</td>
</tr>
<tr>
<td>Total (%)</td>
<td>60</td>
<td>42 (70.0)</td>
<td>18 (30.0)</td>
</tr>
</tbody>
</table>

Figure 3. Overall Survival Curves for hMSH2 Methylated/unmethylated in ALL Patients. Kaplan-Meier survival analysis of hMSH2 methylated group (dotted line) and hMSH2 unmethylated group (solid line) showed a significant difference in survival (log-rank test, *P*<0.0035).

Figure 4. Over-expression of hMSH2 in ALL Cells is Associated with Reduced Growth and Increased Apoptosis. (A) hMSH2 expression was associated with a dramatic reduction in Nalm6 cells growth (*P*=0.0002, t-test) and Reh cell (*P*=0.0006, t-test). Data were the averages from 4 (Nalm6) or 6 (Reh) independent experiments. *P*<0.05 vs 4 days. (B) Apoptosis (determined after Annexin V staining) significantly increased in Reh cells in the presence of hMSH2 expression, but not in Nalm6 cells. Data were averages from 3 independent experiments. *P*<0.05 vs cells transfected with blank vector

positive ALL samples were obtained and assessed for hMSH2 methylation, and cyogenetic data were obtained from previously examined samples. hMSH2 hypermethylation was more common in ETV6-RUNX1 positive ALL samples than that in ALL samples without this fusion gene (75.0% [12/16] vs. 42.5% [17/40], *P*=0.028, [chi-square test]). hMSH2 methylation did not significantly correlate with age, white blood cells, sex, immunophenotype and any other cyogenetic subgroup (Table 4).

To further assess the role of hMSH2 methylation in ALL, 14 samples were collected from adults with relapsed ALL and assessed for hMSH2 methylation. Results showed that almost 12 relapse patients (85.7%) exhibited the hypermethylation of hMSH2 gene, consistent with the possibility that hMSH2 plays a role in chemosensitivity, as seen in vitro experiments. Subsequently, the corresponding diagnostic samples were collected from relapsed patients after treatment, and the hMSH2 methylation was determined. Results demonstrated that hMSH2 methylation significantly increased in the relapse patients when compared with the corresponding diagnostic sample (*P*=0.01). However, the average increase in methylation was relatively small (66% vs. 74%) and this increase was confined to samples with lower methylation levels at diagnosis (samples with <70% methylation at diagnosis showed an average increase of 14% at relapse, *P*=0.001). It is suggested that a combination of high hMSH2 methylation at diagnosis and increased hMSH2 methylation at relapse (especially for samples lacking very high methylation at diagnosis) may result in the extremely high level of hMSH2 methylation seen in relapse samples.

Hypermethylation of hMSH2

hMSH2 expression was assessed using qPCR in 60 samples including 18 unmethylated and 42 hypermethylated samples. Expression was detectable in almost all unmethylated samples, but at low level or absent in methylated samples. The hMSH2 mRNA expression in unmethylated samples was significant different from that in the methylated samples (*P*=0.003, t-test) (Figure 2A).

To further explore the importance of hMSH2 methylation, methylated hMSH2 expression was examined in ALL cell lines. The hypermethylation of hMSH2 was examined in both ALL cell lines, and results showed an absence of methylated hMSH2 expression in both Reh and Nalm6 cell lines which were used for subsequent functional assays. The Nalm6 cells treated with 2'-deoxy-5-azacytidine reduced methylation of the hMSH2 promoter and re-expression of hMSH2 mRNA, demonstrating that DNA methylation of the gene was required for the suppression of expression (Figure 2B).

Prognostic significance of hMSH2 methylation in ALL patients

To test the prognostic value of hMSH2 hypermethylation in ALL patients, the associations between hMSH2 methylation and overall survival was evaluated in ALL patients. In brief, 60 ALL patients were separated into hMSH2 methylation group and unmethylation group. The median survival of patients in hMSH2 methylation group was 22 months, whereas it was 39 months in hMSH2 unmethylation group. Kaplan-Meier survival analysis showed a significant difference between them (log-rank test, *P*=0.0035; Figure 3), indicating that methylation may have both clinical and biologic effects in ALL patients.
Restoration of hMSH2 expression in ALL cells inhibits cell growth and induces apoptosis in Reh cells

To assess the functional significance of hMSH2 in ALL cells, the hMSH2 gene was transfected into Nalm6 cells, in which hMSH2 was epigenetically silenced. As transfection of leukemia cells was generally inefficient, this was done using the pIRE52-eGFP vector, which also expresses eGFP. Following G418 selection, eGFP expressing cells (and thus hMSH2 expressing cells) were subsequently isolated by flow cytometry and eGFP/hMSH2 positive cells (>80% positive) with high purity were collected. hMSH2 expression in this population was confirmed by qPCR. The growth of these cells was then measured within 7 days. As shown in Figure 4A, the hMSH2 expressing cells exhibited a significant decrease in cell growth when compared with untransfected Nalm6 cells or Nalm6 cells transfected with blank vector. Significant inhibition of proliferation was also seen in Reh cells (expressing RUNX1-ETV6 fusion gene) after hMSH2 transfection. It was noted that continued growth in culture of both cell lines resulted in a decline in the fraction of hMSH2 positive cells, presumably due to their lower proliferation rates. This effect was more obvious in Reh cells (levels typically dropped from 70-80% to <50% within 7 days in Reh cells, whereas 3-4 weeks in Nalm6 cells). To determine whether the increased selection against hMSH2 expression was due to the toxicity of hMSH2 in Reh cells, the apoptosis was measured in Nalm6 cells and Reh cells following transient transfection. As shown in Figure 4B, transfection of Nalm6 cells with hMSH2 resulted in only a minor increase in apoptosis as compared to cells transfected with blank vector. In contrast, over-expression of hMSH2 in Reh cells resulted in a significant induction of apoptosis. In addition to negatively regulating cell growth, hMSH2 is shown to negatively influence the survival of ALL cells, but this effect is dependent on the genetic background.

Discussion

Epigenetic inactivation of genes is crucial in the development of leukemia and has dramatic effects on the biological and clinical behaviors of these diseases. DNA methylation is an epigenetic modification that plays an important role in the control of gene expression in mammalian cells, and aberrant DNA methylation plays an important role in the tumor progression (Calvisi et al., 2007; Choi et al., 2007; Shimizu et al., 2007). Many studies have shown that alterations at the genomic levels and regional changes in the patterns of DNA methylation are commonly observed in the neoplasia at early stages (Baylin et al., 1998; Pogribny and James, 2002). Studies have shown that there are highly significant correlation between gene methylation and negative protein expression for mismatch repair hMSH2 (Ward et al., 2003; Ligtenberg et al., 2009; Takeshi et al., 2010; Zhiheng et al., 2012). Herein, our findings showed that the hMSH2 gene was hypermethylated in over half of ALL cases. hMSH2 has been shown to be expressed in normal B lymphocytes. In the present study, our results revealed that hypermethylation of hMSH2 suppressed its expression in both primary cancer and cell lines. Treatment with 2'-deoxy-5-azacytidine resulted in over-expression in Nalm6 cells, demonstrating that the DNA methylation is required for the suppression of hMSH2 expression. Furthermore, functional detection indicated that hMSH2 exhibited multiple important biological effects on ALL cells, including control of cell proliferation and survival.

In early studies, findings revealed that aberrant DNA methylation and epigenetic inactivation of some genes were significantly correlated with the prognosis of ALL (Kuang et al., 2008; Shaoqing et al., 2010). Some studies show that CpG island methylation of hMSH2 is closely related to the prognosis of colorectal cancers (Takeshi et al., 2010; KyungHwa et al., 2011). Few studies have been conducted to investigate the hMSH2 promoter methylation in ALL. Some investigators propose that there’s low hMSH2 expression and high hMSH2 methylation in ALL which is consistent with our previous findings (Caixia et al., 2011). However, no study has been conducted to study the prognostic value of hMSH2 methylation in ALL. Herein, our results showed that aberrant DNA methylation and epigenetic inactivation of hMSH2 decreased overall survival of ALL patients. This means that the early diagnosis of hMSH2 methylation in ALL patients may have prognostic implication, a concept that mandates further exploration in the future.

Over-expression of hMSH2, but not GFP alone, in ALL cells resulted in a dramatic inhibition of cell growth, indicating that hMSH2 can regulate the growth and survival of ALL cells, and hMSH2 has functions similar to those of a tumor suppressor gene. These effects may be due to loss of regulation of RUNX1 or through yet to be identified hMSH2 target proteins. The mechanism by which hMSH2 inhibits cell growth is not yet clear. However, RUNX1 would represent a potential candidate mediator of this effect. Several previous studies have demonstrated that hMSH2 can bind to and inactivate RUNX1 in osteoblasts and myeloid cells. Furthermore, RUNX1 is known to be able to facilitate proliferation of hematopoietic cells and enhance B-cell survival (Cameron and Neil, 2004; Blyth et al., 2009). Consistent with the hypothesis that RUNX1 is a key target for hMSH2, our findings showed that loss of hMSH2 expression in primary ALL was more common in patients with leukemia expressing RUNX1-ETV6 fusion gene. It is likely that hMSH2 binds to the product of this fusion gene, because it retains the hMSH2 binding runt domain (Zelent et al., 2004). The ability of hMSH2 to induce apoptosis was found in the RUNX1-ETV6 positive Reh cells but not in the Nalm6 cells (having no fusion gene, but highly expressing WT RUNX1), suggesting a heightened role for hMSH2 in RUNX1-ETV6 positive leukemia. However, there are likely to be multiple genetic differences between these cell lines and thus the increased apoptosis in Reh cells is not directly linked to the presence of RUNX1-ETV6. We also attempted to confirm the association between loss of hMSH2 expression and presence of RUNX1-ETV6 in ALL by examining publicly available expression database. However, hMSH2 proved to be absent in most array formats used and thus hMSH2 expression cannot be determined. It has been reported that hMSH2 was significantly related to Bcl-2 (Youn et al., 2005). Bcl-2 can suppress DNA mismatch...
repair (hMSH2-hMSH6) with promotion of mutagenesis, which potentially contributes to the genetic instability and carcinogenesis (Yongzhong et al., 2007). In addition, a significant role of hMSH2 in ALL without RUNX1-ETV6 is also observed. Firstly, since over-expression of hMSH2 still produces a very clear inhibition of cell growth in Nalm6 cells, and secondly, hMSH2 hypermethylation is still seen in 42.5% of ALL cases negative for RUNX1-ETV6 (Mrozek et al., 2004). Further studies are required to compare its roles in RUNX1-ETV6 positive and RUNX1-ETV6 negative ALL.

Some investigators proposed a relationship between the expression and methylation of hMSH2 and drug resistance or the response to therapy (chemotherapy and radiotherapy) in cancer patients (Brooks et al., 2003). Hypermethylation of hMSH2 was extremely common in relapsed adult ALL (85.7% of samples), suggesting that treatment preserves either cells with increased CpG island methylation in general or cells with increased hMSH2 methylation in particular. It is also suggested that the pathways regulated by hMSH2 may become targets to reverse the chemoresistance in hMSH2 deficient cells. This may be more important for relapsed ALL adults, who usually exhibit hMSH2 hypermethylation and whose outcome is extremely poor.

In conclusion, our results show relatively frequent aberrant methylation of hMSH2 gene promoter in ALL patients. The aberrant DNA methylation and epigenetic inactivation of hMSH2 play an important role in the occurrence and development of ALL, which is likely related to the alteration of growth and survival of cancer cells.

Acknowledgements

We thank Dr. Yixiong Lei for his helpful suggestions and advice on this manuscript.

References


