Aminopterin (4-amino-4-deoxy-pteroylglutamic acid; NSC 739) was the first drug reported to induce remissions in children with acute leukemia (1). Although aminopterin is a more potent antifolate than methotrexate (4-amino-4-deoxy-10-N-methyl-pteroylglutamic acid; NSC 740; refs. 2–8), it was supplanted by methotrexate in the early 1950s because its toxicity was felt to be unpredictable (4, 6, 7, 9–12). Methotrexate remains a core component of all therapeutic regimens used for patients with acute lymphoblastic leukemia (ALL) and is widely used to treat many other malignant and nonmalignant disorders (13). However, aminopterin may offer advantages over methotrexate, with greater accumulation and metabolism by leukemic blasts in vitro (14) and more complete oral bioavailability (15) than has been reported for methotrexate (16, 17).

Because the most accepted role for an antifolate is not as a single agent, but in the setting of multiagent, post-remission therapy, our goal in the clinical development of aminopterin has been predicated on finding a dose and schedule to mimic the divided-dose oral methotrexate that has been used in post-induction therapy for patients with ALL (18, 19). The maximum tolerated dose of aminopterin on our phase I trial was 2 mg/m²/dose q12 hours for two doses weekly (15). Mucosal toxicity was dose limiting at higher doses and ameliorated by dose reduction and/or the addition of leucovorin rescue. The observed toxicity at the maximum tolerated dose was similar to that observed in patients given methotrexate (25 mg/m²) q6H for four doses weekly as a component of therapy for ALL (18).

This phase II trial was conducted to confirm the bioavailability of oral aminopterin and to determine the antileukemic activity of aminopterin in adult and pediatric patients with refractory acute leukemia; to describe the pharmacodynamic properties of aminopterin; and to contrast the intracellular metabolism of aminopterin and methotrexate by patients’ blasts in vitro.
Materials and Methods

Clinical trial. This was an open-label, single-agent, noncomparative trial to determine if aminopterin is active in the treatment of patients with refractory acute leukemia. Patients were stratified in three treatment groups: stratum 1, children ages <20 years with ALL; stratum 2, adults ages ≥20 years with ALL; and stratum 3, patients of any age with acute myeloid leukemia (AML). Sample size in each stratum was determined using the Gehan two-stage sampling design.

Patients with histologically documented acute leukemia of any subtype, refractory to known effective therapy were eligible. Patients were required to have recovered from all prior acute drug-related toxicity, to have adequate nutritional status (weight above 3rd percentile for age and total serum protein within the reference range), to have adequate hepatic and renal function (total bilirubin <1.5 mg/dL, alanineaminotransferase less than five times the upper limit of normal, serum creatinine normal for age), to have performance status of >50% as measured by the Karnofsky Performance Scale, and to have a predicted life expectancy of >6 weeks. Patients who had previously undergone bone marrow transplantation were required to be at least 3 months from the procedure before enrollment. Patients with severe uncontrolled infections, patients with evidence of significant third-space effusions, patients who have received high-dose methotrexate (>12 times), and pregnant or lactating women were excluded. All patients (or their guardians, in the case of minors) gave signed informed consent, indicating that they were aware of the investigational nature of this study.

Between July 1997 and December 2004, 46 patients were enrolled and treated at five institutions: The Cancer Institute of New Jersey/Robert Wood Johnson University Hospital (New Brunswick, NJ), Children’s Hospital and Regional Medical Center (Seattle, WA), The University of Texas Southwestern Medical Center (Dallas, TX), Columbia University (New York, NY), and the University of Chicago (Chicago, IL). The protocol and informed consent were approved by the institutional review board of each institution.

Materials. Intravenous aminopterin and the oral liquid for oral administration were purified and packaged by Ilex Oncology, Inc. (San Antonio, TX), as previously described (15). The tablet was prepared and packaged by the Cancer Institute of New Jersey. Synthesis of aminopterin tablets was supported in part by a Food and Drug Administration Orphan Products Development grant FD-R-001832-03. Aminopterin was synthesized per the previously reported method of Piper and Montgomery (20), and the powder was pressed into a 1 mg scored tablet by the University of Iowa under IND #49,927. Purity of the aminopterin tablet was assayed at Cancer Institute of New Jersey using isocratic elution on a reverse-phase C18 column, with PDA spectrophotometric detection between 190 and 400 nm. Comparison of the retention time and absorption spectra of individual peaks with known standards showed the aminopterin tablets to be >98% pure aminopterin. Folic acid standards were used to determine the percentage of the tablet, with breakdown products, such as pterins and absorption spectra of individual peaks with known standards showed the aminopterin tablets to be >98% pure aminopterin. Folic acid standards were used to determine the percentage of the tablet, with breakdown products, such as pterins and absorption spectra of individual peaks with known standards showed the aminopterin tablets to be >98% pure aminopterin. Folic acid standards were used to determine the percentage of the tablet, with breakdown products, such as pterins and absorption spectra of individual peaks with known standards showed the aminopterin tablets to be >98% pure aminopterin. Folic acid standards were used to determine the percentage of the tablet, with breakdown products, such as pterins and absorption spectra of individual peaks with known standards showed the aminopterin tablets to be >98% pure aminopterin. 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incubation. Aminopterin was measured as previously described after 24 hours of
otrexate by blasts isolated from patients before treatment with
subsequent 22 patients, who received oral aminopterin only, kinetics were measured after a single oral dose.
Aminopterin concentrations in plasma were determined in the
Pediatric Oncology Laboratory at the Cancer Institute of New Jersey,
using a radioligand binding assay, as previously published (24).
Although the assay was initially developed to measure methotrexate,
aminopterin and methotrexate are equivalent in this competitive
binding assay, with an absolute limit of detection of 0.05 to 0.1 pmol,
depending on the specific activity of the tritiated methotrexate.
Noncompartmental analysis was done to calculate the area under the
curve (AUC), using GraphPad Prism version 4.00 for Windows
(1001 1290 310 9.8 39
1220 y ALL, ALL >20 y ALL, AML
n
Median age (range) 9.7 (1-20) 35.4 (21-61) 46.9 (2.6-73)
Male (%) 50 50 39
T phenotype (%) 12 (55) 1 (10) NA
Median duration of
aminopterin therapy,
wk (range) 4 (1-19) 6 (4-8) 3 (1-8)
NOTE: Patients were enrolled in three strata: children with ALL, adults with
ALL, and all those with AML.
Abbreviation: NA, not applicable.

Table 1. Characteristics of patients enrolled

<table>
<thead>
<tr>
<th>Stratum</th>
<th>ALL, &lt;20 y</th>
<th>ALL, &gt;20 y</th>
<th>AML</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>22</td>
<td>11</td>
<td>13</td>
</tr>
<tr>
<td>Median age (range)</td>
<td>9.7 (1-20)</td>
<td>35.4 (21-61)</td>
<td>46.9 (2.6-73)</td>
</tr>
<tr>
<td>Male (%)</td>
<td>50</td>
<td>50</td>
<td>39</td>
</tr>
<tr>
<td>T phenotype (%)</td>
<td>12 (55)</td>
<td>1 (10)</td>
<td>NA</td>
</tr>
<tr>
<td>Median duration of aminopterin therapy, wk (range)</td>
<td>4 (1-19)</td>
<td>6 (4-8)</td>
<td>3 (1-8)</td>
</tr>
</tbody>
</table>

Due to temporary unavailability of labeled aminopterin and/or insufficient numbers of viable blasts for analysis, accumulation of
[1H]aminopterin and [1H]methotrexate was assayed for only 12 patients on the phase II aminopterin trial. Additional analysis of
intracellular metabolism of methotrexate and aminopterin to poly-
glutamates has also been done using blasts isolated from different
patients (n = 80) with acute leukemia at the time of initial diagnosis,
after institutional review board–approved informed consent was given
to study their blasts. The data reported below includes the results of
analysis of both these newly diagnosed patients (not previously
presented) and those enrolled on the phase II trial of aminopterin.

Results

Patients. Between July 1997 and October 2004, >400
doses of aminopterin were administered to 46 patients
enrolled on this phase II trial. Patient characteristics are
summarized in Table 1; more detailed information regarding
the eight patients who responded to aminopterin is presented in
Table 2. Twenty-seven patients (59%) were White, 10
(22%) were Hispanic, seven (15%) were African American,
and the remaining two were Asian and American Indian,
respectively. Twenty-five patients (54%) completed at least

Table 2. Clinical characteristics of patients who responded to aminopterin therapy

<table>
<thead>
<tr>
<th>Patient ID</th>
<th>Age (y)</th>
<th>Sex</th>
<th>Race</th>
<th>ALL phenotype</th>
<th>Initial treatment regimen</th>
<th>Condition on study entry</th>
<th>CBC on study entry</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>WBC (10^9/μL)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Blasts (cells/μL)</td>
</tr>
<tr>
<td>1001</td>
<td>11</td>
<td>M</td>
<td>AA</td>
<td>T</td>
<td>POG 9086</td>
<td>First relapse; multiagent reinduction failure</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>290</td>
</tr>
<tr>
<td>6004</td>
<td>12</td>
<td>M</td>
<td>W</td>
<td>T</td>
<td>CCG 1961</td>
<td>First relapse; multiagent reinduction failure</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>360</td>
</tr>
<tr>
<td>1007</td>
<td>9</td>
<td>F</td>
<td>AA</td>
<td>T</td>
<td>POG 9404</td>
<td>Induction failure; failed multiple salvage attempts</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td>0</td>
</tr>
<tr>
<td>6012</td>
<td>14</td>
<td>M</td>
<td>AA</td>
<td>pre-B</td>
<td>CCG 1962</td>
<td>Third relapse (first marrow relapse)</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td>0</td>
</tr>
<tr>
<td>3002</td>
<td>8</td>
<td>F</td>
<td>W</td>
<td>pre-B</td>
<td>CCG 1922</td>
<td>Fifth relapse (first marrow relapse)</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>1,000</td>
</tr>
<tr>
<td>1002</td>
<td>19</td>
<td>M</td>
<td>W</td>
<td>T</td>
<td>POG 9086</td>
<td>First relapse; multiagent reinduction failure</td>
<td>2.9</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1,100</td>
</tr>
<tr>
<td>6015</td>
<td>20</td>
<td>M</td>
<td>H</td>
<td>pre-B</td>
<td>DFCI 91-01</td>
<td>First relapse; multiagent reinduction failure</td>
<td>22.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>14,000</td>
</tr>
<tr>
<td>2001</td>
<td>61</td>
<td>M</td>
<td>W</td>
<td>pre-B</td>
<td>CALGB 8811</td>
<td>First relapse; multiagent reinduction failure</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>200</td>
</tr>
</tbody>
</table>

NOTE: Patients were enrolled in three strata: children with ALL, adults with
ALL, and all those with AML.
Abbreviations: AA, African American; W, White; H, Hispanic; Hg, hemoglobin; Plts, platelets.
one full cycle (2 doses/wk \times 4 weeks). With the exception of one adult with AML, who died of systemic infection, those patients who did not complete a full cycle stopped due to disease progression and not toxicity.

One patient was given concurrent hydroxyurea for hyperleukocytosis, in violation of the protocol prohibition against concurrent systemic chemotherapy. This patient received six doses of aminopterin over 3 weeks before being taken off therapy for clinically evident progressive disease. This patient developed grade 3 mucositis. Another patient, a child with pre-B lineage ALL, enrolled twice. She had a clinical improvement during 12 weeks of aminopterin therapy. One year later, she enrolled again but had no response despite 8 weeks of therapy.

Mucosal toxicity. The majority of patients \((n = 27, 59\%)\) experienced no mucositis. Six (13%) developed grade 1 mucositis. Ten (22%) developed grade 2 mucositis. Grade 3 \((n = 1)\) or grade 4 \((n = 2)\) mucositis was seen infrequently \((6\%)\). Twenty-eight patients enrolled after the protocol amendment requiring the addition of leucovorin rescue only for the treatment of grade 2 mucositis. Of these, 16 (57%) required no leucovorin during the first 4 weeks of aminopterin therapy.

Other toxicity. Adverse events while on study were largely due to marrow failure, either secondary to leukemia or the myelosuppressive effect of aminopterin. Nonhematologic toxicities directly related to aminopterin were few in number. One patient with AML developed tumor lysis syndrome during the first week of therapy and died of infectious complications (CTC grade 5 neutropenic sepsis). Three patients developed skin rashes: one with CTC grade 2 erythematous macular rash covering <50% of the body surface, one with varicella zoster (CTC grade 3 infection), and another who suffered a sunburn (CTC grade 2) during a trip to Honolulu. One patient with AML had a deep vein thrombosis (CTC grade 3) that developed in the context of clinical sepsis. Three patients developed asymptomatic grade 2 to 3 hepatotoxicity (serum bilirubin >1.5 and <10 times the upper limit of normal and/or serum aspartate aminotransferase/alanine aminotransferase >2.5 and <20 times the upper limit of normal).

Responses. The highest response rate \((27\%; 95\%\) confidence interval, 8.5-46\%) was seen among children with ALL (Table 3). The time to best response among these children ranged from 8 to 12 weeks. Hematologic variables among those meeting protocol response criteria are shown in Table 4. One of the two children classified as having a partial response \((a 14-year-old African American male with multiply relapsed, pre-B lineage ALL)\) had a bone marrow after his second 4-week cycle that straddled the criteria dividing M1 and M2, with 4% lymphoblasts by morphology and 6% by flow cytometry. With normal peripheral counts and no peripheral blasts, he therefore, might have been considered a complete response if we used the blast counts determined by histology. The response criteria in the protocol, however, did not specify which method should be used to determine blast percentage in the marrow. His bone marrow after the 12th week showed stable disease, with 7% lymphoblasts by flow cytometry. This patient remained on study for a total of 14 weeks, with minimal toxicity before progressing. He required no leucovorin for mucositis until after his 13th week of aminopterin.

Only two adults with ALL, ages 20 and 61 years, both with B-lineage ALL, had clinical improvement during aminopterin therapy, with normalization of peripheral blood counts (Table 4) and the physical examination but no bone marrow examination with <25% blasts. One additional adult with Sézary syndrome and circulating blasts had asymptomatic

<table>
<thead>
<tr>
<th>Table 3. Responses to aminopterin by treatment strata</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stratum</td>
</tr>
<tr>
<td>Progression/no response</td>
</tr>
<tr>
<td>Clinical improvement</td>
</tr>
<tr>
<td>Partial response</td>
</tr>
<tr>
<td>Complete response</td>
</tr>
</tbody>
</table>

NOTE: Patients were evaluated every 4 weeks while on study. Response to aminopterin was defined by changes in peripheral blood counts, physical examination, and bone marrow examination.

<table>
<thead>
<tr>
<th>Table 4. Hematologic responses to aminopterin meeting protocol criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patient ID</td>
</tr>
<tr>
<td>------------</td>
</tr>
<tr>
<td>1001</td>
</tr>
<tr>
<td>6004</td>
</tr>
<tr>
<td>1007</td>
</tr>
<tr>
<td>6012</td>
</tr>
<tr>
<td>3002</td>
</tr>
<tr>
<td>1002</td>
</tr>
<tr>
<td>6015</td>
</tr>
<tr>
<td>2001</td>
</tr>
</tbody>
</table>

NOTE: Complete blood counts and bone marrow blast percentage at time of best response, along with duration of aminopterin therapy and reason for coming off study. Abbreviations: BMT, elective withdrawal from study to undergo allogeneic bone marrow transplantation; PD, progressive disease; CR, complete response; PR, partial response; Impr, improvement; BM, bone marrow; Hg, hemoglobin; Plts, platelets; ANC, absolute neutrophil count.

*Patient 6012 had 4% blasts by histology and 6% bone marrow cells showing the diagnostic aberrant phenotype by flow cytometry, as described in the text.
improvement and remained on therapy for 2 months before electing to enroll in another therapeutic protocol.

Combining the children and adults with ALL, the response rate among patients with T-lineage ALL (two complete response, one partial response, and one improved in 13 patients) was greater than that among those with B-lineage disease (one partial response and three improved in 20 patients). This difference is not statistically significant (P > 0.5, Fisher’s exact test), but this trial was not powered to detect any difference in response among patients with different leukemic subtypes.

There were no responses among 13 patients with AML. As noted above, one patient with AML developed tumor lysis syndrome and pancytopenia after his first dose, suggesting rapid reduction in tumor burden. He died of infectious complications before he could be evaluated for response. Another was on therapy with stable disease for 2.5 months before progressing.

Among patients in each strata, peripheral blast counts tended to decrease during therapy with aminopterin, whereas hemoglobin and platelet counts tended to increase toward normal values (Fig. 1).

**Pharmacokinetics.** A comparison of the pharmacokinetics after i.v. and oral administration was done in the first 24 patients (Fig. 2). In patients with matched i.v. and oral pharmacokinetics, no significant difference in AUC was observed, with mean oral bioavailability of 96.8%. Among all patients, the mean AUC (±SE) after oral administration was 0.52 ± 0.04 µmol hour/L, which is not statistically different from that seen after administration of i.v. aminopterin at the same dose (2 mg/m²) on the phase I trial (15). Pharmacokinetic analysis revealed no significant difference between the tablet (n = 16) and liquid formulations (n = 29) in AUC.

No significant difference was seen between those patients with clinical responses to aminopterin and those who did not respond, in mean peak serum aminopterin concentration (0.166 ± 0.018 versus 0.167 ± 0.035 µmol/L) or AUC (0.48 ± 0.04 versus 0.40 ± 0.06 µmol hour/L).

**Accumulation of aminopterin and methotrexate polyglutamates in vitro.** Earlier reports have related clinical outcome with methotrexate accumulation by leukemia blast cells, either incubated with 1 µmol/L in vitro or after an infusion of methotrexate before the start of standard therapy (i.e., an in situ incubation; refs. 26, 27). We therefore assessed [³H]methotrexate and [³H]aminopterin accumulation and metabolism in blast cells whenever sufficient cell numbers were available before therapy. Those patients with clinical responses to aminopterin tended to show greater accumulation of [³H]aminopterin by their leukemic blasts in vitro (mean ± SE: 0.79 ± 0.19 pmol/10⁶ cells; n = 6) than those who did not respond (mean: 0.41 ± 0.09 pmol/10⁶ cells; n = 6; P = 0.09, two-tailed t test).

To contrast accumulation and metabolism by blasts of different leukemic types, blasts from patients on this phase II trial (n = 12) as well as others with newly diagnosed leukemia (n = 80) have been tested and the data combined. After 24 hours of incubation with either 1 µmol/L [³H]methotrexate or 0.1 µmol/L [³H]aminopterin, there was no significant difference in total accumulation between blasts from patients with pre-B phenotype ALL, T-lineage ALL, and AML (Table 5). As noted by others (28–30), we find differences in the degree to which each leukemia subtype converts methotrexate to polyglutamates. Lymphoblasts from patients with pre-B ALL are better able to metabolize methotrexate to methotrexate polyglutamates than T lymphoblasts, and both groups of patients’ lymphoblasts metabolized more methotrexate than myeloblasts (Table 5). In contrast, aminopterin was metabolized consistently to polyglutamates by both lymphoblast subsets (median polyglutamate fractions of 100%), and the drop-off in

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**Fig. 1.** Hematologic responses to aminopterin therapy. Blood counts were measured at least weekly during therapy with aminopterin. Points, mean; bars, SE. Peripheral blast counts (A) tended to decrease during therapy with aminopterin. In contrast, hemoglobin (B) and platelets (C) tended to increase.

**Fig. 2.** Aminopterin pharmacokinetics. Mean serum aminopterin concentration after an oral (n = 41, □) or i.v. (n = 28, △) dose of 2 mg/m². Mean AUC ± SE was 0.52 ± 0.03 and 0.51 ± 0.03 µmol hour/L after oral and i.v. dosing, respectively. Points, mean; bars, SE.
the myeloblasts was smaller than that seen for methotrexate. Within each subset, the percentage of aminopterin found as a polyglutamate was significantly greater than the corresponding methotrexate polyglutamate fraction ($P < 0.05$ for each comparison, two-tailed Mann-Whitney $U$ test).

After a high-performance liquid chromatography separation, interesting differences between the distribution of intracellular aminopterin and methotrexate polyglutamates were also noted. In lymphoblasts from patients with B-lineage ALL, methotrexate polyglutamates from glu$_2$ through glu$_4$ are found in increasing frequency with increasing chain length, whereas the corresponding aminopterin polyglutamates are found in decreasing frequency (Fig. 3A). However, for both aminopterin and methotrexate, long-chain polyglutamates ($\geq$3 glutamate residues) exceed 60% of the total intracellular antifolate pool.

The pattern of aminopterin polyglutamates in pre-B ALL blasts differs dramatically from that seen in T-phenotype ALL or AML (Fig. 3B and C), where aminopterin-glu$_3$ predominates and little longer-chain aminopterin is seen (<30% of the total). It is striking that under similar conditions, the natural ligand methyl tetrahydrofolate is metabolized completely to very long-chain polyglutamates, predominantly -glu$_5$-7 (data not shown).

### Discussion

Aminopterin was replaced by methotrexate in the 1950s, because the latter had a better therapeutic index in murine models (31), and the clinical toxicity of aminopterin was less predictable (4, 6, 7, 9–12). No randomized clinical trial was done to compare the two antifolates. In retrospect, aminopterin may have been discarded prematurely. The erratic clinical toxicity of aminopterin five decades ago may have been the result of variable contamination with folate (32, 33), providing unpredictable degrees of rescue. This problem has been eliminated in more modern preparations. We confirm the purity of the aminopterin tablets at least quarterly using three methods: UV spectrum, radioligand binding assay using dihydrofolate reductase and radiolabeled methotrexate, and high-performance liquid chromatography. When we found significant decomposition of the initial liquid preparation over 3 years from initial formulation, the impurity seemed to be folic acid. In 4 years, this decomposition has not yet been observed with the tablet.

In the early era of antifolate chemotherapy (1948-1951), as many as 66% of newly diagnosed patients responded to daily oral or i.m. aminopterin (1). Clinical resistance to antifolates upon relapse was also described (4, 5, 10, 11), and much of the biochemical basis for antifolate resistance has been elucidated over the subsequent decades (34, 35). We initially brought aminopterin back to the clinic, because laboratory data suggest that it may offer advantages over methotrexate for some patients with ALL. At identical extracellular concentrations, more aminopterin than methotrexate is accumulated by blasts from patients with pre-B ALL, T-lineage ALL, and AML (14). In addition, less interpatient variability is observed in the degree of metabolism of aminopterin to aminopterin polyglutamates than of methotrexate to methotrexate polyglutamates. It is likely that both of these observations are explained by differences in affinity for folylpolyglutamyl synthase, the enzyme that catalyzes the sequential addition of glutamate residues to folate and classic antifolates, effectively trapping them within the cell. Aminopterin has 20-fold greater affinity than methotrexate for folylpolyglutamate synthase than methotrexate and a higher ratio of $V_{\text{max}}/K_m$ (36–38).

Excellent oral bioavailability of aminopterin was observed in the phase I trial (15), a finding confirmed in this phase II trial. In addition, we note that the interpatient variability in oral pharmacokinetics (coefficient of variation = 34.7%; $n = 26$) is less than that which has been observed for methotrexate (up to 59%), at approximately equipotent doses (16, 17, 39).

We now describe for the first time the distribution of aminopterin polyglutamates after metabolism by patients’ leukemic blasts. Consistent with earlier data with murine cells (40, 41), diglutamate predominance was observed in blasts from patients with T-phenotype ALL or AML. However, we note that in blasts from patients with B-lineage ALL, longer chain polyglutamates (aminopterin-glu$_{2-5}$) were seen with a frequency similar to that of the diglutamate. The reasons for this lineage-specific difference in aminopterin polyglutamylination are not clear. With methotrexate as a substrate, quantitative

### Table 5. Accumulation and metabolism of aminopterin and methotrexate by patients’ leukemic blasts

<table>
<thead>
<tr>
<th>Antifolylpolyglutamate (extracellular concentration)</th>
<th>$n$</th>
<th>Total intracellular antifolylpolyglutamate ($\mu$mol/10$^6$ cells), median (range)</th>
<th>% Found as antifolylpolyglutamate</th>
<th>Median (range)</th>
<th>Compared with Pre-B ALL ($P$)</th>
<th>Aminopterin compared with methotrexate ($P$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methotrexate (1 $\mu$mol/L) Pre-B ALL 52</td>
<td>0.64 (0.06-3.55)</td>
<td>96 (28-100)</td>
<td>---</td>
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<td>---</td>
</tr>
<tr>
<td>Pre-B ALL 21</td>
<td>0.65 (0.09-2.01)</td>
<td>89 (6-100)</td>
<td>$&lt;0.05$</td>
<td>---</td>
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<td>---</td>
</tr>
<tr>
<td>Pre-B ALL 19</td>
<td>0.45 (0.16-3.56)</td>
<td>69 (44-100)</td>
<td>$&lt;0.01$</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>T-ALL 13</td>
<td>0.33 (0.08-1.90)</td>
<td>100 (83-100)</td>
<td>---</td>
<td>$&lt;0.01$</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>T-ALL 13</td>
<td>0.38 (0.11-1.17)</td>
<td>100 (73-100)</td>
<td>NS</td>
<td>$&lt;0.05$</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>T-ALL 13</td>
<td>0.35 (0.14-0.51)</td>
<td>97 (36-100)</td>
<td>$&lt;0.05$</td>
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</tr>
<tr>
<td>Aminopterin (0.1 $\mu$mol/L) Pre-B ALL 24</td>
<td>0.33 (0.08-1.90)</td>
<td>100 (83-100)</td>
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<td>Aminopterin (0.1 $\mu$mol/L) Pre-B ALL 12</td>
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<td>---</td>
</tr>
</tbody>
</table>

NOTE: Bone marrow leukemic blasts isolated from patients were incubated with 1 $\mu$mol/L [3H]methotrexate or 0.1 $\mu$mol/L [3H]aminopterin in vitro. After 24 hours, the cells were collected, washed, and lysed. An aliquot was counted scintillation counter to determine total accumulation, expressed as pmol/10$^6$ viable cells. Antifolylpolyglutamates were separated from the parent compounds by high-performance liquid chromatography and compared with known, unlabeled standards.

Abbreviations: B-ALL, B-lineage ALL; T-ALL, T-phenotype ALL; NS, not significant.

Unpublished data.
differences in polyglutamylation between B-lineage ALL and T-phenotype ALL or AML have been related to quantitative differences in folic polyglutamate synthase expression (29, 42, 43) and to qualitative differences in folic polyglutamate synthase affinity for methotrexate (44).

The differences we observed between aminopterin and methotrexate polyglutamylation profiles in leukemic blasts raise a paradox. It is generally accepted that longer chain folic polyglutamates or antifolic polyglutamates are preferentially retained within the cell longer and are more toxic (45–47). However, at equimolar extracellular concentrations, steady-state aminopterin accumulation is greater than that of methotrexate (14), despite a shorter average polyglutamate chain length.

It is possible that there is a disparity in the affinities of aminopterin and methotrexate for efflux mechanisms. It is notable that although aminopterin polyglutamates had shorter average chain length than methotrexate polyglutamates in blasts of each leukemic subtype, conversion of the parent compound to at least the diglutamate was more consistent for aminopterin than methotrexate. Metabolism to even the diglutamate form is known to significantly retard cellular efflux of classic antifolates like methotrexate and aminopterin (40). Methotrexate but not methotrexate diglutamate is a substrate for efflux pumps, such as the human multidrug resistance proteins MRP3 (48) and MRP4 (49). In addition to affecting efflux rates, the different pattern of intracellular polyglutamate profiles might cause differences between the two antifolates in inhibition of target enzymes or subcellular localization. Ongoing studies in our laboratory are addressing these questions.

With greater cellular accumulation and metabolism, more reliable bioavailability than methotrexate, and tolerable toxicity at this dose and schedule, aminopterin deserves further study as a potent alternative to methotrexate. Our current results show aminopterin retains significant activity among children with refractory ALL. Greater response rates, among untreated patients, were seen historically (1, 3, 5, 6) when aminopterin was given on a daily schedule at lower doses (0.5-1 mg i.m. daily × 5 for up to 3 weeks), not much greater than the RDA for folic acid. As noted above, the dose and schedule used on this trial (4 mg/m²/wk in two divided doses, 12 hours apart) were developed explicitly for the purpose of inclusion in post-induction multiagent therapy. It is possible that patients with refractory ALL would benefit from a trial reexploring the earlier aminopterin regimen. For now, based on these data, we are testing whether aminopterin can be safely substituted for systemic methotrexate after induction in multiagent therapy for children with newly diagnosed ALL at high risk of relapse (50).

Fig. 3. Intracellular antifolylpolyglutamates formed in vitro by patients’ leukemic blasts. Bone marrow leukemic blasts isolated from patients at initial diagnosis were incubated with 1 μmol/L [3H]methotrexate or 0.1 μmol/L [3H]aminopterin in vitro. After 24 hours, the cells were collected, washed, and lysed. Antifolylpolyglutamates were separated by high-performance liquid chromatography and compared with known, unlabeled standards. For each polyglutamate species, the mean fraction of the total intracellular antifolate is indicated. Columns, mean; bars, SE.

A, accumulation by leukemic blasts from patients with B-lineage ALL. B, accumulation by leukemic blasts from patients with T-lineage ALL. C, accumulation by leukemic blasts from patients with AML.

References


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