Leukocyte \( O^6 \)-Alkylguanine-DNA Alkytransferase from Human Donors Is Uniformly Sensitive to \( O^6 \)-Benzylguanine

Stanton L. Gerson, Jane Schupp, Lili Liu, Anthony E. Pegg, and Sankar Srinivasen
Division of Hematology/Oncology and the Ireland Cancer Center at Case Western Reserve University and University Hospital of Cleveland, Cleveland, Ohio 44106 [S. L. G., J. S., L. L., S. S.], and Department of Physiology, Pennsylvania State University School of Medicine, Hershey, Pennsylvania 17033 [A. E. P.]

ABSTRACT

\( O^6 \)-Alkylguanine-DNA alkyltransferase (AGT) is the key DNA repair protein responsible for resistance to chloroethylating and methylating agents that attack at the \( O^6 \) position of guanine. \( O^6 \)-Benzylguanine (BG), a potent inhibitor of AGT, has recently entered clinical trials. A number of point mutations and at least one human polymorphism within AGT are associated with AGT resistance to inactivation by BG. In this study, we evaluated AGT inhibition by BG in an in vitro assay of peripheral blood mononuclear cell AGT from 56 normal donors, 42 Caucasians, and 14 Japanese. AGT activity ranged of peripheral blood mononuclear cell AGT from 56 normal study, we evaluated AGT inhibition by BG in an associated with AGT resistance to inactivation by BG. In this study, we evaluated AGT inhibition by BG in an in vitro assay of peripheral blood mononuclear cell AGT from 56 normal donors, 42 Caucasians, and 14 Japanese. AGT activity ranged.

INTRODUCTION

The DNA repair protein AGT\(^3\) is the key protein responsible for repair of chemotherapy and carcinogen-induced DNA adducts at the \( O^6 \) position of guanine (1). High levels of AGT correlate with resistance to a number of chemotherapy agents, including BCNU, dacarbazine, procarbazine, streptozotocin, and temozolomide (1–3), protect against the carcinogenic effects of methylating agents in animal models (4). Low levels of AGT predict sensitivity to these agents (5). Recently, a new therapeutic inhibitor of AGT, BG, has been described. BG sensitizes AGT expressing, BCNU-resistant tumors both in vitro and in xenograft models and is nontoxic at therapeutic concentrations (6, 7). Ongoing clinical trials have shown that it is possible to completely inhibit human AGT in patient peripheral blood mononuclear cells (8) and in tumors (9). We have documented, using sequential deep tissue tumor biopsies, 100% depletion of human tumor AGT at doses of 120 mg/m\(^2\) BG, which produced maximum serum concentrations of 15 \( \mu \)M BG.

The wild-type AGT is remarkably sensitive to inhibition by BG, with an \( ED_{50} \) of about 0.5 \( \mu \)M in cell extracts (10). However, mutations in certain regions of AGT confer resistance to BG. For instance, the bacterial AGT protein derived from the ada gene (11), is remarkably resistant to BG but has similar capacity to remove \( O^6 \)-mG adducts compared with that of human AGT (12). By point-directed mutagenesis, a number of amino acids that differ between ada and the human AGT gene, MGMT, when introduced into MGMT result in resistance to BG (13–15). Some mutant AGTs have reduced reactivity with \( O^6 \)-mG or are unstable (15). The recent description of a polymorphism in the Japanese population at codon 160 of MGMT, a glycine to arginine mutation, gly160arg, (16), and the verification that this polymorphism resulted in a 20-fold increase in the \( ED_{50} \) for BG (17) raised concerns that polymorphisms in MGMT may be common and if present, could result in partial resistance to BG, which could impact significantly on clinical efficacy of BG as a modulator of AGT.

MATERIALS AND METHODS

Heparinized blood was collected after informed consent from normal volunteer Caucasian and Japanese donors. The mononuclear layer from 40 ml of blood was obtained after Ficoll-Hypaque isopyknic gradient and processed for alkyltransferase (AGT) activity as described previously (18, 19).

This laboratory has reported lymphocyte AGT from normal donors since 1985 and has developed a method to standardize activity measurements over many years that allows us to relate measurements performed in 1985 (18) with those performed in 1998 (20–22). Key components of this standardization procedure include a single method of measurement using direct assay of residual \( O^6 \)-mG adducts on a substrate DNA, standardization of the substrate made from \([\text{H}]\text{MNU}\)-treated calf thymus DNA...
with direct comparison between old and new substrates, and use of AGT enzyme standards with each assay that have been from the same source over the entire time period.

RESULTS

In this study population of 56 donors, baseline peripheral blood mononuclear cell AGT varied 10-fold, from 2.7 to 21.9 fmol/μg DNA. The activity was not significantly related to age or gender. The AGT activity was similar in the Caucasian (7.1 ± 3.6 fmol/μg DNA, n = 42) and Japanese (8.9 ± 4.4 fmol/μg DNA, n = 14) groups. The overall range of activity was similar to that which we have reported previously in peripheral blood mononuclear cell AGT for >13 years in >300 samples (9, 19–22) and is the same range of peripheral blood mononuclear cell AGT activity seen in over 130 additional patient and normal donor samples analyzed in our laboratory that remain unreported. In none of these samples have we observed AGT of <1.5 or >32 fmol/μg DNA. Most importantly, we have never observed a human mononuclear sample with no AGT activity (limit of detection, 0.05 fmol/μg DNA, corresponding to ~180 molecules/cell). As we have reported previously, AGT measurement on the basis of cellular DNA is preferred because it allows better comparison to other tissues that have different relative amounts of DNA and protein (19), and because in peripheral blood mononuclear cell preparations, red cell contamination may sometimes increase the amount of apparent protein that is not derived from mononuclear cells. Because red cells contain negligible amounts of AGT, this can lead to a falsely low estimate of AGT. Although we have data (which is available) for all samples in units of activity/mg cellular protein, we will not report it here.

To measure BG inhibition of AGT activity, an amount of cellular extract representing a fixed amount of enzyme activity, as determined by baseline enzyme assay, was incubated with BG in a concentration range of 0, 0.05, 0.2, 0.5, 1, 2, and 4 μM before adding [methyl-3H]calf thymus DNA. The amount of cellular protein used was 50 fmol (0, 0.05, and 0.2 μM BG) or 200 fmol (0.5, 1, 2, and 4 μM BG) of activity, depending upon the concentration of BG used. One BG stock solution in DMSO was used for all reaction concentrations, keeping final DMSO concentrations to 1% or less in the reactions. The reaction was preincubated for 30 min at 37°C, after which residual AGT activity was determined by adding [methyl-3H]calf thymus DNA substrate. AGT inactivation at each concentration was determined as the percentage of baseline activity. ED50 and ED90 values were obtained for each donor sample. AGT depletion by 30 min exposure to BG of extracts of these blood mononuclear cells was consistent in all samples. Fig. 1A indicates that a similar pattern of AGT inactivation was observed in samples from Caucasian and Japanese groups. As shown in Table 1, the mean ED50 for BG in the Caucasian donors was 0.37 ± 0.09 μM, n = 42, and among Japanese donors was 0.36 ± 0.11 μM, n = 14. Mean ED90 for BG in the Caucasian donors was lower, 1.06 ± 0.29 μM, n = 42, than in Japanese donors, 1.52 ± 0.51 μM, n = 14, P = 0.002. The distribution of ED50s is shown in Fig. 1B and is independent of baseline AGT. Similar data were obtained for the ED90s. No outliers were evident, and all have ED50s were <0.8 μM BG.

To estimate the situation in which a donor mononuclear cell preparation expressed AGT from two different alleles, both wild-type AGT protein and AGT gly160arg protein carrying the Japanese polymorphism of position 160, we mixed either wild-type AGT protein and AGT gly160arg protein carrying the Escherichia coli transformant-derived AGT gly160arg protein (17). The aliquots of equal activity of AGTs (50 fmol activity for the purified wild-type or gly160arg mutant AGT, or a mixture of 25 fmol of wild-type with 25 fmol of gly160arg or mononuclear cell ex-
tracts) were pre-incubated with different concentrations of BG at 37°C for 30 min in assay buffer containing 50 μg of calf thymus DNA. The residual AGT activity was determined by incubating the samples with [3H] methylated DNA for 30 min at 37°C. The ED50 reflected the presence of the BG-sensitive wild-type protein (ED50, 1.3 μM) and the BG-resistant gly160arg AGT (ED50, 24 μM). In the mixture of purified proteins, the ED50 was 17 μM. For the mixture containing mononuclear cell extract and wild-type purified AGT, the ED50 was 1.8 μM, and with BG-resistant mutant AGT, the ED50 was 9 μM. These values were much higher than the ED50 and ED90 values we observed in any of the donor samples, indicating that there was no sample with a high degree of BG resistance.

**DISCUSSION**

This study indicates that inactivation of AGT by BG is very uniform in a sample of 56 normal donors in the United States, including 42 Caucasians and 14 Japanese. No outliers with increased sensitivity or resistance to BG were seen, and there was no correlation between baseline AGT and BG inactivation in individual donors. These studies were undertaken because of a number of reports about the presence of polymorphisms in AGT, which could render the protein resistant to BG. Such polymorphisms, if prevalent in the population, could impact on the therapeutic efficacy of BG. Imai (16) reported that a polymorphism in the AGT gene. We observed that in any of the donor samples, indicating that there was no sample with a high degree of BG resistance.

The tact we took, analysis of BG sensitivity, is quite different than a search for polymorphisms in the MGMT gene. We wanted to determine whether there was a functional difference in AGT among individuals, i.e., whether we could detect differences in AGT based on analysis of AGT activity in lymphocytes. From this we would infer that these BG-resistant AGT reflected germ-line mutations in the MGMT gene. We observed no such functional polymorphism among 56 donors and conclude that ED50 values of >1 μM BG are uncommon (95% confidence interval, 0–6%).

A final issue that remains in the assessment of altered AGT sensitivity to BG is whether AGT mutations that are BG resistant are present in patient tumors, although they may not be germ line. These could arise either during the transformation process, perhaps due to genomic instability, or be acquired during drug treatment. We have reported in preliminary form the acquisition of resistance to BG and BCNU in MCF-7 breast cancer cells (27) and colon cancer HCT116 cells (28) after repeated exposure to these agents. The MCF-7 cells resistant to BG and BCNU have normal AGT activity and normal AGT sensitivity to BG, suggesting that in these cells, resistance is not due to an alteration in AGT. In HCT116, however, data suggest that the cell has a mutated AGT with less reactivity toward O6-mG and markedly increased resistance to BG.4 This suggests that tumors might acquire resistance to BG and BCNU through mutation in the MGMT gene. Whether this occurs clinically and is responsible for acquired resistance to BG and BCNU remains to be evaluated.

**REFERENCES**


4 L. Liu et al., unpublished results.
Human Alkyltransferase Sensitivity to O6-Benzylguanine


Leukocyte $\text{O}^6$-Alkylguanine-DNA Alkyltransferase from Human Donors Is Uniformly Sensitive to $\text{O}^6$-Benzylguanine

Stanton L. Gerson, Jane Schupp, Lili Liu, et al.


Updated version  Access the most recent version of this article at: http://clincancerres.aacrjournals.org/content/5/3/521

Cited articles  This article cites 27 articles, 17 of which you can access for free at: http://clincancerres.aacrjournals.org/content/5/3/521.full.html#ref-list-1

Citing articles  This article has been cited by 2 HighWire-hosted articles. Access the articles at: /content/5/3/521.full.html#related-urls

E-mail alerts  Sign up to receive free email-alerts related to this article or journal.

Reprints and Subscriptions  To order reprints of this article or to subscribe to the journal, contact the AACR Publications Department at pubs@aacr.org.

Permissions  To request permission to re-use all or part of this article, contact the AACR Publications Department at permissions@aacr.org.