Potentiation of the Antimitochondrial and Antiproliferative Effects of Bis(guanylhydrazones) by Phenethylbiguanide

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ABSTRACT

The ability of methylglyoxal-bis(guanylhydrazone) (MGBG) and 4,4'-diacetyldiphenylurea-bis(guanylhydrazone) to interact with the hypoglycemic agent, phenethylbiguanide (DBI), in affecting the bioenergetic functions of isolated rat liver mitochondria was studied. DBI was found to increase markedly the inhibitory effect of either 4,4'-diacetyldiphenylurea-bis(guanylhydrazone) or MGBG on respiration of isolated rat liver mitochondria. Conversely, these bis(guanylhydrazones) enhanced the inhibitory potency of DBI and increased the apparent affinity of mitochondria for the drug. As with MGBG and 4,4'-diacetyldiphenylurea-bis(guanylhydrazone), the potassium cationophore, valinomycin, increased the sensitivity of mitochondrial respiration to DBI. It is suggested that the enhancement of bis(guanylhydrazone) inhibition of mitochondrial respiration by DBI involves inhibition of proton fluxes across the inner mitochondrial membrane and the subsequent alkalization of the mitochondrial matrix. This drug interaction was extended to the level of antiproliferative activity in which DBI was found to potentiate the growth-inhibitory effects of MGBG on murine L1210 leukemia in vivo.

INTRODUCTION

Several of the bis(guanylhydrazones) have gained recognition for their antiproliferative activity in experimental and clinical settings (22). The best known in this regard is the aliphatic derivative, MGBG5 (Chart 1), which has been used clinically in the treatment of lymphoma and leukemia (15, 16, 36). Although the aromatic bis(guanylhydrazone), DDUG (Chart 1), displayed a 20 times greater therapeutic index than did MGBG against animal tumors, it demonstrated limited activity in clinical trials (22).

At present, the molecular mechanism responsible for the antiproliferative action of these bis(guanylhydrazones) remains uncertain. The drugs differ in their effectiveness at certain intracellular sites with growth-inhibitory potential. MGBG is a potent inhibitor of S-adenosylmethionine decarboxylase, a key enzyme in spermidine and spermine biosynthesis, while DDUG is without effect (8). By contrast, DDUG binds tightly to linear DNA and inhibits DNA polymerase while MGBG is only weakly active in these effects (10, 11). Recently, it has been found that both MGBG (25, 28) and DDUG (24) have in common the ability to interfere profoundly with structure and function of mitochondria. With both drugs, this action is apparent at growth-inhibitory drug concentrations and occurs prior to detectable inhibition of growth or decrease in cell viability (29, 31).6 On the basis of these and other considerations (30),7 it is proposed that the mitochondrial effects caused by MGBG and DDUG contribute significantly to the antiproliferative action of these drugs.

The effects of MGBG and DDUG on the bioenergetic functions of isolated rat liver mitochondria have been characterized recently (6). At mM concentrations, MGBG inhibits markedly State 4 respiration but only slightly affects State 3 or uncoupled respiration. In terms of concentration, DDUG is 18 times more effective than MGBG in this action. On the basis of permeability studies and microelectrophoresis of isolated mitochondria, it was concluded that MGBG and DDUG act by neutralizing the surface potential of the inner mitochondrial membrane and by interfering with cation fluxes across that membrane. The basis for the differential effect of MGBG and DDUG on mitochondria according to their metabolic state is thought (6) to be due to electrophoretic attraction of the drugs to the mitochondrial membrane during State 4 respiration by the transmembrane potential. According to the chemiosmotic theory (26), this effect would only exist during State 4 respiration and not State 3 or uncoupled respiration.

The overall effects of bis(guanylhydrazones) on isolated mitochondria are comparable in many respects to those obtained with the biguanides, particularly the hypoglycemic agent DBI (12, 14, 32, 33). It seems probable, therefore, that an interaction might exist between these agents at the level of the mitochondrion. The present data indicate that the effects of MGBG and DDUG on the respiration of isolated rat liver mitochondria are, in fact, potentiated by DBI. Moreover, DBI was found to enhance the antileukemic action of MGBG in an additive fashion. While the findings could have clinical relevance, they also support our contention (30) that mitochondrial effects may be responsible for the antiproliferative action of MGBG and DDUG.

MATERIALS AND METHODS

MGBG was obtained from the National Cancer Institute (Bethesda, Md.). DDUG and DBI were obtained from Ciba Research Laboratories (Basel, Switzerland) and Ciba-Geigy (Summit, N. J.), respectively. Mitochondrial substrates were obtained from Sigma Chemical Co. (St.

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5 The abbreviations used are: MGBG, 1,1'-(methylethanediylidene)dinitrilo diguanidine (also known as methylglyoxal-bis(guanylhydrazone)); DDUG, 4,4'- diacetyldiphenylurea-bis(guanylhydrazone); DBI, 1-phenethylbiguanide (also known as phenformin); DNP, 2,4-dinitrophenol; CCCP, carbonylcyanide-m-chlorophenylhydrazone.

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6 D. L. Kramer and C. W. Porter, unpublished data.
7 A. Wiseman, D. Kramer, and C. W. Porter, Human cell variants resistant to the antiproliferative effects of methylglyoxal-bis(guanylhydrazone), submitted for publication.
treated with slightly inhibitory (1 mM) or even noninhibitory concentrations of DDUG were added to mitochondria pre-treat activity, while at higher concentrations (>0.3 mM) it strongly inhibits respiration. DBI, by contrast, has no effect at concentrations (<0.2 mM) stimulates State 4 respiratory activity, see Table 1. We have shown previously (6) that DDUG and MGBG enhanced the inhibitory effect of DBI on respiration with DDUG being more effective in this regard. From the double-reciprocal plot of DBI inhibitory ability versus concentration (Chart 3), it seems that MGBG and DDUG increased significantly the inhibitory potency of DBI and the apparent KI at high concentrations (>2.0 mM). Similarly, pretreatment of mitochondria with even noninhibitory concentrations (1 mM) of DBI enhanced the inhibitory potency of DBI. }

Table 1 summarizes the various dose-dependent interactions of DDUG, MGBG, and DBI on the inhibition of State 4 respiration. At noninhibitory concentrations, both MGBG and DDUG enhanced the inhibitory effect of DBI on respiration with DDUG being more effective in this regard. From the double-reciprocal plot of DBI inhibitory ability versus concentration (Chart 3), it seems that MGBG and DDUG increased significantly the inhibitory potency of DBI and the apparent KI at high concentrations (>2.0 mM). Similarly, pretreatment of mitochondria with even noninhibitory concentrations (1 mM) of DBI enhanced the inhibitory potency of DBI.

RESULTS

State 4 respiration of isolated rat liver mitochondria was inhibited by DDUG, DBI, or MGBG (given in order of effectiveness, see Table 1). We have shown previously (6) that DDUG at low concentrations (<0.2 mM) stimulates State 4 respiratory activity, while at higher concentrations (>0.3 mM) it strongly inhibits respiration. DBI, by contrast, has no effect at concentrations lower than that required to inhibit respiration (1.4 mM) and is similar to MGBG in this respect. When stimulatory concentrations of DDUG were added to mitochondria pre-treated with slightly inhibitory (1.4 mM) or even noninhibitory (1 mM) concentrations of DBI, a marked inhibition of State 4 respiration occurred (Chart 2A and B). This inhibition was not influenced by the subsequent addition of either DNP or CCCP (Chart 2A), whereas respiratory inhibition imposed by DBI alone was reversed by the uncoupling agent (Chart 2C). When the drug sequence was reversed (i.e., stimulatory concentrations of DDUG followed by DBI), an inhibition of respiration occurred which was not reversible with DNP (Chart 2D). The addition of either DDUG or DBI to mitochondria uncoupled with DNP or CCCP had little effect on oxygen utilization (Chart 2, D and G). However, when both DBI and DDUG were present, marked inhibition of uncoupled respiration was apparent (Chart 2, F and G). Qualitatively, similar effects were obtained with either succinate (plus glutamate) or glutamate alone as substrate.

Table 1

<table>
<thead>
<tr>
<th>Pretreatment</th>
<th>Inhibitor</th>
<th>I50 for inhibitor (mM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>MGBG</td>
<td>6.00</td>
</tr>
<tr>
<td>0.3 mM DDUG</td>
<td>MGBG</td>
<td>1.50</td>
</tr>
<tr>
<td>1 mM DBI</td>
<td>MGBG</td>
<td>1.33</td>
</tr>
<tr>
<td>None</td>
<td>DDUG</td>
<td>0.33</td>
</tr>
<tr>
<td>1 mM DBI</td>
<td>DDUG</td>
<td>0.19</td>
</tr>
<tr>
<td>4 mM DBI</td>
<td>DDUG</td>
<td>0.17</td>
</tr>
<tr>
<td>2.5 mM MGBG</td>
<td>DDUG</td>
<td>0.18</td>
</tr>
<tr>
<td>None</td>
<td>DBI</td>
<td>1.40</td>
</tr>
<tr>
<td>2.5 mM MGBG</td>
<td>DBI</td>
<td>0.85</td>
</tr>
<tr>
<td>0.3 mM DDUG</td>
<td>DBI</td>
<td>0.30</td>
</tr>
</tbody>
</table>

I50 is calculated as the inhibitor concentration causing 50% inhibition of respiratory activity assuming 100% activity before inhibitor addition.

Interactions of Bis(guanylhydrazones) and DBI
litory activity of DDUG or MGBG (Table 1). Comparable interac-
tions were also noted between DDUG and MGBG with either
bis(guanylhydrazone) enhancing the potency of the other. By
contrast, pretreatment of mitochondria with the polyamines
putrescine, spermidine, or spermine actually protected mito-
chondrial respiration from the inhibitory actions of DBI, DDUG,
or MGBG (data not shown).

The presence of valinomycin in the medium increases sig-
ificantly the inhibition of mitochondrial respiration by DBI.
From the double-reciprocal plot of DBI inhibitory action versus
concentration (Chart 4), it appears that valinomycin enhanced
the inhibitory potency of DBI without altering the apparent K,
for the drug.

In the studies testing the antileukemia action of DBI, MGBG,
and their combination, the untreated mice bearing L1210 leu-
kemia cells died 9 days after tumor cell inoculation (Table 2).
Treatment of mice with MGBG alone resulted in a prolongation
of survival time by 4.5 days with no evidence of toxicity at the
maximum sequential dose of 50 mg/kg. DBI at 40 or 80 mg/
kg increased the survival time by slightly more than 2 days.
The drug combination of MGBG at 25 mg/kg and DBI at 80
mg/kg was the most effective among those tested and resulted
in a 66% (6-day) increase in life span. When MGBG was used
in the drug combination at 50 mg/kg, toxicity was encountered
as evidenced by an increase in mortality. Overall, the com-
bination of DBI and MGBG at the optimum drug concentrations
appears to be an additive interaction with respect to antileu-
kemic activity.

DISCUSSION

The present data demonstrate that, at the level of isolated
rat liver mitochondria, DDUG and MGBG interact with DBI to
inhibit State 5 respiration in a synergistic manner. Pretreatment
of mitochondria with noninhibitory concentrations of either
bis(guanylhydrazone) permits marked inhibition of respiration
by concentrations of DBI that are otherwise ineffective when
added alone. Similarly, when the reverse situation is applied,
DBI permits inhibition of mitochondrial respiration by ineffective
concentrations of DDUG or MGBG. The double-reciprocal plot
of DBI dose-dependent inhibition suggests that this synergism
is the consequence of both enhanced DBI inhibitory potential
and greater binding of DBI to mitochondria, as indicated by the
increased K, (Chart 3).

Inhibition of mitochondrial respiration by DBI was also in-
creased by valinomycin, a cationophore specific for potassium
(Chart 4). The nature of this drug interaction at the level of
mitochondria was distinctly different from that of DBI with either
bis(guanylhydrazone). The latter drug combination decreased
markedly the apparent K, for DBI (Chart 3), whereas the com-
bination of DBI and valinomycin did not (Chart 4), suggesting
different mechanisms for increased respiratory inhibition.

It is interesting that valinomycin enhanced the inhibition of
respiratory by DBI while classical uncouplers, such as DNP or
CCCP, did not (Chart 2). The latter act by dissipating the proton
gradient across the inner mitochondrial membrane, while vali-
nomycin increases potassium fluxes across the membrane
which is usually followed by an equal and opposite movement
of protons (27). These 2 processes, potassium fluxes and
proton ejection, are believed to be inhibited by DBI (32). Thus,
respiration stimulated by valinomycin appears to be more sen-
sitive to DBI than does respiration uncoupled by DNP or CCCP,
which apparently is not dependent on processes affected by
DBI. It is suggested that the enhancement of bis(guanylhydra-
zone) inhibition of mitochondrial respiration by DBI involves
inhibition of proton fluxes across the inner mitochondrial mem-
brane with possible subsequent alkalinization of the mitochon-
drial matrix.

From the antileukemic data, it is apparent that the interaction
of DBI and MGBG in inhibiting mitochondria also exists with
respect to antiproliferative activity, at least as additivity (Table
2). At optimum drug concentrations, DBI increased the antileu-
kemic effects of MGBG by about 30%, which is not quite as
much as that caused by pretreatment of mice with a-difluoro-
methylornithine (2). The latter is an extremely specific inhibitor
of ornithine decarboxylase (18), which has no significant mi-
 tochondrial effects (30). Unlike DBI, it enhances MGBG cyto-
toxicity by depleting tissues of spermidine and thereby increas-
ing their uptake of MGBG (1), which utilizes the spermidine carrier mechanism (9). We suggest that the increased uptake with α-difluoromethylornithine leads to increased inhibition of mitochondrial function.

Several of the biguanides, in addition to being hypoglycemic agents, have potential in cancer chemotherapy. DBI potentiates the antitumor effects of cyclophosphamide and hydrazine sulfate (13) and 1,3-bis(2-chloroethyl)-1-nitrosourea (7). The antidiabetic agent, decamethyleneguanidine (also known as Synthalin), inhibits the growth of L1210 leukemia and Sarcoma 180 cells in vivo (23), and the action of MGBG on transplanted mouse leukemia is potentiated by the biguanides, stillbamidine, hydroxystilbamidine, and decamethyleneguanidine (2, 3, 20, 21).

Whether or not the DBI enhancement of antitumor activity of cyclophosphamide and hydrazine sulfate (13) or 1,3-bis(2-chloroethyl)-1-nitrosourea (7) are also related to drug interactions at the level of the mitochondrion seems unlikely since the action of these latter drugs is not thought to involve that organelle. In the case of the bis(guanylhydrazones), however, there is increasing evidence (6, 29, 30) that the antiproliferative action may be related to their effects on mitochondria. Certainly, the data presented here showing synergistic drug effects at the level of the mitochondrion and additive effects in antileukemic activity by the drug combination is supportive of a casual relationship. Moreover, recent studies (19, 30) indicate that the seemingly high concentrations of MGBG used in these experiments with mitochondria are actually comparable to those achieved intracellularly by a variety of cell types exposed to growth-inhibitory (10 μM) concentrations of drug (34).

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