Evaluation of the in Vivo Antitumor Activity and In Vitro Cytotoxic Properties of Auranofin, a Coordinated Gold Compound, in Murine Tumor Models

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ABSTRACT

The coordinated gold compound, 2,3,4,6-tetra-O-acetyl-1-thio-\(\beta\)-d-glucopyranosato-S-triethylphosphine gold (auranofin; Ridaura), is a p.o.-K.M., S. T.C.] and Department of Pharmacology, University of Pennsylvania [C.K.M., S. T.C.J, Philadelphia, Pennsylvania 19104; and Department of Pharmacology, Baylor College of Medicine [S.T.C.], Houston, Texas 77030

INTRODUCTION

Auranofin [2,3,4,6-tetra-O-acetyl-1-thio-\(\beta\)-d-glucopyranosato-S-triethylphosphine gold(I); Ridaura SKF D-39162] is a p.o.-absorbed gold complex shown to be active in the treatment of rheumatoid arthritis (3, 22). This drug has been shown to inhibit human lymphocyte responsiveness both in vivo (7, 24) and in vitro (5). More recently, there have been a number of reports on the in vitro antiproliferative effects of auranofin on a variety of animal and human tumor cell lines in vitro (4, 11, 12, 20). Auranofin has also demonstrated potent cytotoxic activity in the primary tumor clonogenic assay against a variety of human tumor types.\(^2\) In vivo antitumor activity has also been reported for auranofin against P388 mouse leukemia (21).

To better define the potential antitumor activity of auranofin, we have studied its effects in a variety of in vitro and in vivo systems (4, 11). In this paper, we describe the evaluation of antitumor activity of auranofin in a panel of mouse tumor models and present the results of in vitro studies which were designed to evaluate the possible mechanisms of the cytotoxic activity of the drug.

1 To whom requests for reprints should be addressed.
2 D. Von Hoff and C. K. Mirabelli, unpublished results.

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Cell Culture Techniques

B16 melanoma cells (highly metastatic subline, F10) (14) were maintained as monolayer cultures in MEM* (Grand Island Biological Co., Grand Island, NY) supplemented with 10% calf serum and 1% penicillin-streptomycin in a 5% CO2-humidified incubator at 37°.

In Vitro Cytotoxicity Assays

Monolayer Clonogenic Assay. Asynchronous populations of cells were harvested and replated at 5000 cells/plate in sterile 60 x 15-mm Petri plates. Plates were incubated overnight to allow attachment of cells to the plate surface. Cells were treated with auranofin for 2 hr in either the presence or absence of 10% FCS (as indicated) in MEM under sterile conditions followed by aspiration of medium. Plates were washed one time with 5 ml of PBS, followed by addition of 5 ml of fresh medium. Plates were incubated for 5 days at 37° in a CO2 incubator. Viability was measured by the ability of a cell to form a colony greater than 50 cells. Colonies were fixed with 0.5% crystal violet in 95% ethanol. Plates were dried and counted with a Biotron III automatic count totalizer (New Brunswick Scientific Co., Edison, NJ). The mean ± S.D. of triplicate samples was determined for each drug concentration. The data were analyzed by plotting the log of the survival fraction (number of colonies in drug-treated plates/number of colonies in controls) versus the drug concentration.

Cell Cycle Analysis. The effects of auranofin on cell cycle progression of logarithmically growing B16 melanoma cells were analyzed by measurements of relative DNA content of individual cells. Cells were fixed with ethanol, stained with mithramycin, and analyzed using a fluorescence-activated cell sorter (Coulter Electronics, Inc., Hialeah, FL) as described previously (18).

Logarithmic and plateau growth phases were obtained by harvesting confluent monolayers of B16 cells and replating at 7.5 x 10⁵ cells/plate. Cells were then incubated at 37° in 5% CO₂ and the number of cells/plate was monitored for each group of plates. The plates with an initial concentration of 7.5 x 10⁵ cells/plate reached a plateau at a concentration of 4 x 10⁶ cells/plate at 50 hr through 90 hr, whereas the cells plated at 1 x 10⁶ cells/plate were in exponential growth phase from 20 hr through 90 hr. Thus, exponentially growing cells were selected from plates initially plated at 1 x 10⁶ cells/plate and treated with auranofin at 37° after plating, whereas plateau-phase cells were represented by those in plates, which were initially plated at 7.5 x 10⁵ cells/plate and treated with auranofin at 70 hr postplating. Following 2 hr of drug incubation, the cells were harvested with trypsin, counted, and replated at 5000 cells/plate, and the percentage of survival was determined.

Inhibition of Macromolecular Synthesis. Logarithmically growing cells were harvested with tetradsodium EDTA (versene), washed once, and resuspended in fresh medium at a concentration of 1.1 x 10⁶ cells/ml. One hundred µl of a drug-containing medium were added to 900 µl of cell suspension. The cell suspensions were incubated at 37° for 1 hr with continuous shaking. [3H]Leucine (3 µCi/ml), [3H]thymidine (1 µCi/ml), or [3H]uridine (1 µCi/ml) was added, and incubations were continued for 2 hr. Immediately after incubation, the cell suspensions were put on ice, and TCA was added to a final concentration of 10%. Thirty min after TCA addition, the mixture was filtered through glass microfiber filters (Whatman, London, England) using a sampling manifold (Millipore Corp., Bedford, MA). The filters were then dried and placed into scintillation vials with 5 ml of Econofluor (New England Nuclear, Boston, MA), and incorporation of [3H]-precursors into the TCA-precipitable materials was measured in a Beckman LS 9800 counter (Beckman Instruments, CA). Inhibition of the precursor uptake into macromolecules was measured as a percentage of the control samples (cells incubated with [3H]-precursors in the absence of a drug), and IC50 values were calculated.

Vital Dye Exclusion. Logarithmically growing cells were harvested with versene and resuspended in fresh medium. Cells were then exposed to auranofin for increasing time periods or with increasing concentrations at 37° and 0°, and the ability of cells to exclude trypan blue (Sigma) was measured. Cells in medium were mixed with an equal volume of 0.2% trypan blue in PBS, and the number of cells excluding the dye was scored using a Leitz microscope (x40). In experiments in which the clonogenic capacity was compared to the ability of cells to exclude dye, aliquots of cells were removed before addition of the dye, washed 2 times in PBS, and replated for the monolayer clonogenic assay.

Cell Association of 195Au from 195Au-labeled Auranofin. Asynchronous populations of B16 cells were treated with versene and resuspended in fresh medium at 10⁶ cells/ml. One-half ml of medium containing auranofin (195Au labeled, 31.9 µCi/mmol) was added to 0.5 ml of cell suspension. Following incubation under the conditions specified in "Results," the cells were transferred to glass microfiber filters in a sampling manifold and were then washed 5 times with cold PBS. Filters were placed in scintillation vials, and the cell-associated radioactivity was determined in a Beckman Gamma 8000 counter (Beckman Instruments, Irvine, CA).

Extraction of Non-Protein-associated Gold from Medium. Two µm (7.7 x 10⁶ dpm) auranofin (195Au) were added to medium containing FCS at concentrations between 0 and 10%. Following 5 min of incubation at 0°, 100 µl of the mixtures were then added to 400 µl of toluene in microfuge tubes (1.5 ml). The mixture was incubated for 5 min on ice with vortexing at 1-min intervals. The tubes were then centrifuged in a microfuge (Beckman Instruments, Irvine, CA) for 5 min. The toluene layer was removed, and the aqueous layer was again extracted with 400 µl of toluene. The 2 toluene extracts were pooled, and the 195Au in both the toluene and medium was measured by γ counting. Protein-associated gold is not extracted into the toluene.

RESULTS

In Vivo Antitumor Activity of Auranofin. The activity of auranofin against i.p. P388 leukemia is shown in Chart 1. The dose response presented is a composite of 30 experiments with auranofin administered i.p. on Days 1 through 5 following i.p.

<chart>

Chart 1. In vivo antitumor activity of auranofin (0) in i.p. P388 leukemia. Tumor-bearing animals were treated with drug on Days 1 through 5 with a single daily dose i.p. Median survival times were measured at each dose, and net log cell kill was determined as described in "Materials and Methods." Points, mean of 30 assays; bars, S.E.

* The abbreviations used are: MEM, minimal essential medium; PBS, phosphate-buffered saline; TCA, trichloroacetic acid; FCS, fetal calf serum; ILS, increasable(d) life span; MTD, maximum tolerated dose; IC50, drug concentration required to reduce cell survival by 50% on the exponential part of the survival curve.

4 J. Dent, personal communication.
tumor implantation. The optimal dose of auranofin, 12 mg/kg, produced an average of 59% ILS. Reduction of the dose to 6 mg/kg resulted in an average of 51% ILS. Cisplatin was included as a positive control in these experiments and produced an average of 117% ILS at the optimal dose of 2 mg/kg.

Table 1 shows the results of experiments in which the schedule dependency of auranofin in the treatment of i.p. P388 leukemia was evaluated. The results of the first experiment indicate that auranofin is slightly more effective administered daily than when given at a 2-day interval and is significantly less effective when given on the every fourth day schedule. This may be a reflection of the fact that the maximally tolerated dose is not increased by lengthening the interval between doses. The effects of increasing the number of injections per day on both the potency and activity of auranofin were determined (Table 1, Experiment 2), since administration of auranofin twice daily had been shown by Simon et al. (21) to be more effective than daily treatment. The results of these experiments indicate that increasing the number of injections per day decreased the MTD per injection with a similar total daily MTD. In contrast to the results presented by Simon et al. (21), the maximum ILS achieved on the split-dose schedules was essentially identical to results achieved with single daily doses. Conversion of the dose-response data from Experiment 2 to cell kill is shown in Chart 2, which shows that decreasing interval between treatments at each of the doses tested produced a decreased in the amount of cell kill achieved. For example, treatment of the tumor with 2 mg/kg once a day for 5 days produced a log net cell kill of 0.33 with each treatment, whereas treatment with 2 mg/kg 2, 4, and 8 times per day achieved net log cell kills of 0.17, 0.09, and 0.06, respectively.

The antitumor activity of auranofin was also evaluated in a variety of mouse solid tumor model systems. These included M5076 reticulum cell sarcoma (implanted i.p. or s.c.), B16 melanoma (implanted i.p. or s.c.), Madison 109 lung carcinoma (implanted i.p. or s.c.), colon carcinoma 26 (implanted i.p. or s.c.), Lewis lung carcinoma (implanted i.p. or s.c.), and mammary adenocarcinomas 16/c and 13/c (implanted s.c.). Auranofin was administered i.p. In each of the above tumor models, auranofin neither prolonged life span nor inhibited the growth of s.c.-implanted tumors. Auranofin was also evaluated in mice bearing i.v. P388 leukemia, and the drug was inactive when administered i.p., i.v., or s.c.

As shown in Table 2, the activity of auranofin against i.p. P388 leukemia is evident only when the drug is administered i.p. Auranofin, given i.v., s.c., or p.o., was essentially inactive in P388 leukemia regardless of dose level.

**Effects of Auranofin on Tumor Cells In Vitro.** The ability of auranofin to inhibit the growth of cells in vitro has been reported by several investigators (1, 5, 20). We have reported previously that auranofin is as cytotoxic or more cytotoxic to a number of tumor cell lines in vitro as a number of clinically used antitumor agents (11). The following studies were performed to better define the mechanism(s) by which this drug inhibits the growth of cells in vitro.

The effect of auranofin on the clonogenic capacity of B16 melanoma cells following a 2-hr treatment is shown in Chart 3A. The survival curve was monophasic and exponential. The cytotoxic potency of auranofin against P388 leukemia and B16 melanoma cells was equivalent as determined in the clonogenic assay with the cells grown in soft agar (data not shown). Chart 3B shows that the cytotoxic effect of auranofin on B16 cells was also dependent on the duration of treatment. Unlike the effects of varying concentrations, the survival curves generated in the time course studies were biphasic with a more rapid rate of cell kill through 2 hr, followed by a less rapid rate through the next 22 hr.

The ability of B16 melanoma cells to exclude trypan blue as a function of auranofin treatment was evaluated and compared to clonogenicity (Chart 4). The response to auranofin treatment as measured by both end points was exponential and monophasic. Although the slopes of the survival curves appeared to differ,
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Chart 3. Cytotoxic activity of auranofin against B16 melanoma cells as measured in the monolayer clonogenic assay. A, colony formation as a function of auranofin concentration following a 2-hr exposure to drug in the presence (•) and absence (○) of 10% FCS; B, colony formation as a function of the exposure time of cells to auranofin at 1 (•) and 4 μM (○). Points, mean of 3 assays; bars, S.E.

the IC50 values were not significantly different. The effect of auranofin on cell viability measured by trypan blue exclusion was found to be temperature dependent. As described in Chart 5, the IC50 following 2-hr exposure at 37°C was 15-fold lower than that at 0°C.

Cell Cycle Analysis. Flow cytometric analysis of B16 melanoma cells treated with auranofin indicated no drug-induced progression delay; treatment of the cells with auranofin (0.0125 μM) for 24 hr allowed for greater than 90% cell survival and produced no changes from the control pattern (no drug) in the DNA distribution histograms. At concentrations of auranofin above 0.2 μM, extensive cell lysis occurred with debris accumulating in the lower channels of the histograms, but the overall distribution of cells in the G1, S, and G2-M compartments was not altered significantly from untreated populations (data not shown).

To determine whether auranofin showed any selective cyto-
toxicity towards cycling versus noncycling cells, both logarithmic and plateau phase populations of B16 cells were prepared and treated with drug for 2 hr at 37°, and their clonogenic capacity was determined. The resulting survival curves were both exponential with equivalent IC50 values (stationary cell population, 6.5 ± 1.0 μM; logarithmic cell population, 7.0 ± 0.8 μM).

**Effect on the Incorporation of 3H-labeled Precursors into DNA, RNA, and Protein.** The effects of auranofin on the incorporation of 3H-labeled precursors into DNA, RNA, and protein were compared with those of 3 known specific inhibitors of macromolecular syntheses (Table 3). Auranofin inhibited the uptake of all 3 precursors into TCA-insoluble materials. However, unlike the 3 standard agents, auranofin showed no significant preferential inhibitory effect on either DNA, RNA, or protein synthesis. Although auranofin appeared to inhibit DNA synthesis at the lowest concentration, the IC50 values for the inhibition of synthesis of the various macromolecules were similar to those which rendered the cells permeable to trypan blue under similar experimental conditions (Chart 4).

**Association of Gold from Auranofin with B16 Melanoma Cells.** The association of auranofin-derived gold with cells in vitro was measured using 199Au-labeled auranofin in a filter binding assay as described in "Materials and Methods." Under conditions identical to those used in the cytotoxicity studies shown in Chart 4 (i.e., 2-hr incubation; 37°, 10% PCS; and 5 x 105 cells), the cellular association of 199Au was linearly proportional to the auranofin concentration with no evidence of saturation up to 20 μM auranofin (Chart 6A). At cytotoxic IC50 concentrations measured by the clonogenic and vital dye exclusion assay (2 to 5 μM), the amount of cell-associated gold was in the range of 4 x 10-18 to 9 x 10-18 mol of gold per cell. Cell volume was measured under these conditions and found to be 2.0 ± 0.2 x 10-12 liters (data not shown). Therefore, at the experimentally measured IC50 concentrations, the cell-associated gold concentration was between 200 and 450 μM, approximately 100-fold higher than the extracellular concentration of auranofin. The level of cell-associated gold increased as a function of time for 10 min and reached a plateau at 15 min (Chart 6B). After incubation for 30 min, the amount of cell-associated gold corresponded to approximately 25% of the total amount of gold added at the beginning of the incubation. Association of gold from auranofin with cells was temperature dependent, with approximately a 7-fold greater amount of gold associated with cells after 30 min when incubated at 37° as compared to 0°.

**Dissociation of the gold from the cells was measured as described in "Materials and Methods."** As shown in Chart 7, cells preincubated with 2 μM auranofin retained 95% of the initially bound gold during the 1-hr incubation in fresh medium. However, addition of 2-mercaptoethanol to the postincubation medium resulted in a decrease in the amount of cell-associated gold. These results are consistent with the postulated interaction of auranofin with the cell via gold-sulfhydryl linkage at either the membrane or intracellular level (15).

**Effect of Serum on the Cytotoxic Potency and Cellular Gold Binding.** The cytotoxic potency of auranofin in vivo was significantly reduced when cells were incubated with the compound in the presence of FCS. The IC50 for a 2-hr auranofin exposure, as measured by the clonogenic assay, was approximately 10-fold higher in the presence of 10% FCS as compared to drug exposure in medium not containing FCS (Chart 3A).

The amount of gold associated with cells following incubation with auranofin was also affected by the presence of serum in the incubation medium. In the presence of 10% FCS, the initial rate at which the gold became associated with the cells and the steady-state level of cell-associated gold were decreased (Chart 4).

Extraction of the incubation medium with toluene, which removes free auranofin and other non-protein-associated forms of auranofin-derived gold, revealed that increasing the concentrations of FCS reduced the concentration of toluene-extractable gold. In medium free of FCS, 95% of the gold from auranofin could be extracted into toluene. Increasing concentrations of FCS decreased the amount of extractable gold (Chart 9). At an auranofin concentration of 2 μM, only 10% of the gold was extractable in the presence of 10% FCS.

**DISCUSSION**

In a previous study, Simon et al. (21) reported that auranofin was effective in increasing the life span of mice inoculated with lymphocytic leukemia P388. In their study, auranofin was administered i.p. every fourth day, daily, and twice per day for a 9-day course of treatment. The drug was least effective given every fourth day (40% ILS) and most effective given twice per day (120% ILS). In our studies, auranofin was less effective against P388 leukemia, and we did not find that multiple daily treatment resulted in increased antitumor activity. The multiple dosing experiments shown in Table 1 indicate that dosage fractionation does not permit the administration of a higher total daily dose of auranofin nor does it result in an improvement in the antitumor activity of the drug.

Although auranofin appears to kill cells in vitro in a log-linear fashion with respect to concentration (first-order cell kill, Chart 2), there is a definite plateau in the cell kill curve determined from in vivo experiments (Chart 1). On the daily treatment schedule, the maximum cell kill achieved is about 0.6 log at 8 mg/kg. There is no increase in cell kill at 16 mg/kg, even though this dose is well tolerated by mice. Another characteristic of the cell kill kinetics of auranofin in vivo is the decrease in cell kill at any particular dose level with shorter intervals between doses of the drug. Although speculative at present, this could be due to a time-dependent tolerance (tachyphylaxis) induced by auranofin in surviving cells [e.g., induction of metallothionein (13, 17)] or, based on studies with serum in vitro, a transient enhancement of albumin levels in peritoneal fluid induced by auranofin treatment.

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<tr>
<th>Compound</th>
<th>IC50 (μM) for precursor uptake into TCA-precipitable material</th>
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<tr>
<td></td>
<td>[3H]Thymidine</td>
</tr>
<tr>
<td>Aphidicolin</td>
<td>0.3 ± 0.03</td>
</tr>
<tr>
<td>Actinomycin D</td>
<td>3 ± 0.5</td>
</tr>
<tr>
<td>Acetylcycteineimide</td>
<td>0.09 ± 0.01</td>
</tr>
<tr>
<td>Auranofin</td>
<td>6 ± 0.4</td>
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* Mean ± S.E.

Table 3

**Inhibition of DNA, RNA, and protein synthesis as measured by uptake of precursors into TCA-precipitable material**

B16 cells were incubated for 1 hr with compound and then for 2 hr with compound and [3H]-precursor, and TCA was precipitated and then counted.

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Our studies included an extensive evaluation of the antitumor activity of auranofin in a spectrum of mouse tumor models. Of these, only i.p. P388 leukemia responded to this drug. While this drug would appear to have a very limited spectrum of in vivo antitumor activity, it possesses potent in vitro cytotoxic activity against a variety of tumor cell lines (4, 11, 12, 20). Our data suggest that auranofin does not alter cell cycle distribution or preferentially kill cells in logarithmic growth as do many cytotoxic antineoplastic agents. While the drug did inhibit DNA, RNA, and protein syntheses, the inhibition was not selective and occurred at concentrations which were acutely lethal to cells as measured by trypan blue exclusion. The equivalent IC50 values, as measured in the clonogenic and dye exclusion assays (Chart 4), along with the data outlined above, suggest a rapid cellular response to the cytotoxicity of auranofin unlike the more delayed response observed for cytotoxic antitumor agents, such as Adriamycin and actinomycin D (1). This rapid response was evident microscopically as cells treated at auranofin concentrations as low as 1 μM for 2 hr showed extensive morphological alterations including surface membrane pitting, cell rounding, detachment from the surface of the culture dish, and membrane lysis. Together, these data suggest that the rapid cellular response to the cytotoxic action of auranofin is due to its effects on cellular processes other than DNA, RNA, or protein synthesis.
with a variety of structural analogues of auranofin have identified the phosphine-gold moiety of the molecule as being required for in vitro cytotoxic and in vivo antitumor activities.

Serum proteins, especially serum albumin, play an important but poorly understood role in the disposition of a number of drugs and certain metals (23), including gold(I) thiolates. The binding of gold to serum albumin during chrysotherapy (8) following the in vivo administration of gold complexes to animals (10) and during the in vitro incubation of gold complexes with serum (2, 9) or purified protein (6) has been clearly demonstrated. As shown by our studies, increasing the concentration of FCS resulted in a decrease in the cytotoxic potency of auranofin (Chart 3A) and a proportional increase in protein-associated gold (Chart 3B). This suggests that the cytotoxic action of the drug results from the non-protein-bound form of gold from auranofin.

However, the extent of cell-associated gold in the presence of FCS (Chart 8) indicates that the gold from gold-protein complexes can become associated with the cells. For example, when cells were incubated with 2 μM auranofin, the inclusion of 10% FCS in the incubation medium produced an approximate 10-fold decrease in cytotoxic potency and the level of nonprotein gold, but only a 2- to 3-fold decrease in cell-associated gold (relative to those values measured in the absence of FCS). Our data also show that auranofin gold associated with cells is stable and does not dissociate within 1 hr in drug-free medium (Chart 7). The ability of 2-mercaptoethanol and dithiothreitol (not shown) to dissociate the cell-associated gold suggests a thiol-reversible interaction of the gold at either the membrane or intracellular level.

In conclusion, the in vivo antitumor activity of auranofin as evaluated in a spectrum of mouse tumor models is extremely limited. However, this drug has potent cytotoxic activity in vitro against a variety of tumor cell types. The data presented in this paper demonstrate that the cytotoxic effect of the drug is rapid and that there appears to be a direct relationship between cellular association of auranofin-derived gold and the cytotoxic effect of the drug. In addition, this cytotoxic effect is not mediated through a cell cycle-specific or -dependent mechanism nor is there evidence for a preferential inhibition of DNA, RNA, or protein synthesis. Further evaluation and definition of the cellular interactions of auranofin may lead to the design of a cytotoxic gold complex with a greater degree and spectrum of antitumor activity as well as additional insights into the cellular pharmacology of clinically established gold complexes in rheumatoid arthritis.

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