An NQO1- and PARP-1-mediated cell death pathway induced in non-small-cell lung cancer cells by β-lapachone

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Lung cancer is the number one cause of cancer-related deaths in the world. Patients treated with current chemotherapies for non-small-cell lung cancers (NSCLCs) have a survival rate of ~15% after 5 years. Novel approaches are needed to treat this disease. We show elevated NAD(P)H:quinone oxidoreductase-1 (NQO1) levels in tumors from NSCLC patients. β-Lapachone, an effective chemotherapeutic and radiosensitizing agent, selectively killed NSCLC cells that expressed high levels of NQO1. Isogenic H596 NSCLC cells that lacked or expressed NQO1 along with A549 NSCLC cells treated with or without dicoumarol, were used to elucidate the mechanism of action and optimal therapeutic window of β-lapachone. NSCLC cells were killed in an NQO1-dependent manner by β-lapachone (LD50, ~4 µM) with a minimum 2-h exposure. Kinetically, β-lapachone-induced cell death was characterized by the following: (i) dramatic reactive oxygen species (ROS) formation, eliciting extensive DNA damage; (ii) hyperactivation of poly(ADP-ribose)polymerase-1 (PARP-1); (iii) depletion of NAD+/ATP levels; and (iv) proteolytic cleavage of p53/PARP-1, indicating μ-calfap activation and apoptosis. β-Lapachone-induced PARP-1 hyperactivation, nucleotide depletion, and apoptosis were blocked by 3-aminobenzamide, a PARP-1 inhibitor, and 1,2-bis(2-aminoethoxy)ethane-N,N,N′,N′′-tetraacetic acid (BAPTA-AM), a Ca2⁺ chelator. NQO1+ cells (H596, IMR-90) or dicoumarol-exposed NQO1−A549 cells were resistant (LD50, >40 µM) to ROS formation and all cytotoxic effects of β-lapachone. Our data indicate that the most efficacious strategy using β-lapachone in chemotherapy was to deliver the drug in short pulses, greatly reducing cytotoxicity to NQO1− “normal” cells. β-Lapachone killed cells in a tumor-selective manner and is indicated for use against NQO1+ NSCLC cancers.

DNA repair inhibitor | non-small-cell lung cancer | NQO1 | apoptosis | μ-calfap cell death

Lung cancer is responsible for nearly one-third (29%) of all cancer-related deaths in the United States (1). Current therapies for non-small-cell lung cancer (NSCLC), which represents >80% of all lung cancers, use platinum-based drugs (e.g., cisplatin) in combination with ionizing radiation (2). Although progress has been made, the long-term survival of NSCLC patients remains bleak at ~15% 5 yr after therapy (2). There is a great need to develop tumor-selective chemotherapeutic agents specific for NSCLCs.

Elucidation of novel cell death pathways for selective killing of chemoresistant NSCLC tumors may lead to more effective treatment strategies. Currently, there are no developed chemotherapeutic agents that exploit poly(ADP-ribose)polymerase-1 (PARP-1) hyperactivation for NSCLC therapy. PARP-1 facilitates DNA repair, specifically in rescaling DNA single-strand breaks (3). PARP-1 binds and stabilizes DNA single-strand breaks, and then converts NAD+ (its substrate) into branched poly(ADP-ribose) (PAR) polymers that are used to postranslationally modify itself and other specific protein substrates. When DNA damage overwhelms repair (e.g., after severe genotoxic stress), PARP-1 becomes hyperactivated. PARP-1 hyperactivation leads to rapid NAD+ depletion, dramatic ATP pool losses, and cell death referred to as “programmed necrosis” (4) or “necroptosis” (5, 6). Such cell death responses have been noted only after supralethal N-methyl-N′-nitro-N′-nitrosoguanidine or hydrogen peroxide (H2O2) doses (7).

β-Lapachone (β-lap) (3,4-dihydro-2,2-dimethyl-2H-naphth[1,2-b]pyran-5-6-dione) is an antitumor agent with renewed interest because of its selective killing of human cancer cells that overexpress endogenous NAD(P)H:quinone oxidoreductase-1 (NQO1) (E.C. 1.6.99.2), a two-electron oxidoreductase (8). The development of novel delivery strategies that increase the bioavailability and tumor targeting of β-lap have further served to peak interest in its use as an antitumor agent (9–12). In fact, ARQ 501 (i.e., β-lap) is currently in phase II trials against pancreatic cancers.

Importantly, β-lap kills cancer cells regardless of cell cycle position (5, 6) or p53 status (6). It synergizes with ionizing radiation (13, 14) or selective chemotherapies (11), highlighting the compound’s usefulness for cancer therapy. Here, we generated isogenically matched NQO1+ and NQO1− human H596 NSCLC cells and demonstrated that β-lap induces PARP-1-mediated cell death in an NQO1-dependent manner, an exploitable pathway for selective therapy of NSCLCs.

Results

Specific Elevation of NQO1 in NSCLC Determines β-Lap Lethality. Prior data suggested that NQO1 expression was elevated in tumors of...
In C alone (ND). (H9252 treated with various we generated isogenically matched H596 cells expressing or Bey et al. Kong databases showed that NQO1 mRNA levels were elevated (15, 16). Analyses of microarray data from New York and Hong Kong tissue banks were analyzed for NQO1 mRNA levels as described in Materials and Methods. Numbers above bars indicate the number of patients examined (Fig. 2). DIC dramatically prevented ROS in A549 cells (Fig. 2 A Right and B Right). In contrast, β-lap-exposed NQ− H966 cells showed little to no ROS formation at all doses examined (Fig. 2 A Left and B Left). Exposure of H596 or A549 cells with 2 mM H2O2 resulted in elevated ROS levels independent of NQO1 expression.

**β-Lap Induces NQO1-Dependent DNA Damage.** Dramatic ROS induction suggested that β-lap exposure may cause damage and breaks in DNA. DNA damage, measured by comet tail formation, was detected in NQ+ H596 and A549 NSCLC cells after β-lap exposure (10 μM, 2 h) (Fig. 1). DNA damage was not detected in NQ− H596 cells, nor in DIC-treated A549 or NQ− H966 cells (Fig. 2C). Thus, NQO1-mediated ROS formation led to significant DNA breaks not observed in cells lacking this enzyme (Fig. 2C). Exposure of all cells to 2 mM H2O2 caused equivalent DNA damage (Fig. 2C).

**β-Lap-Induced PARP-1 Hyperactivation Depletes Essential Nucleotides.** We previously noted a rapid loss of ATP during β-lap-stimulated cell death in a process leading to μ-calpain activation (18). Because the combination of DNA damage and nucleotide (ATP) loss was observed during high dose H2O2- or N-methyl-N'-nitro-N-nitrosoguanidine-induced cell death responses involving PARP-1 hyperactivation (19), we examined the role of this repair protein in β-lap-induced lethality. PAR accumulation, an indicator of PARP-1 hyperactivation, was detected in NQ+ H966 and A549 cells in 10 min of 10 μM β-lap exposure (Fig. 3 A Left and B Left). DIC suppressed PAR formation in β-lap-exposed A549 cells (Fig. 3 B Right), whereas NQ− H966 cells exposed to β-lap did not elicit PAR formation (Fig. 3 A Right). In contrast, H2O2 (2 mM) exposure of all cells tested resulted in significant and comparable PAR formation (Fig. 3 A and B).

Rapid PAR-polymer formation correlated well with loss of essential metabolic nucleotides (i.e., ATP and NAD+ in both NQO1+ H956 and A549 cells (Fig. 3 C and D). Abrogation of NQO1 function, either by genetic polymorphism or by DIC (50 μM) addition, prevented β-lap-induced PAR formation and nucleotide loss (Fig. 3).
Inhibition of PARP-1 activity using 3-aminobenzamide (3-AB), an NAD⁺ analog, spared NQO₁⁺ H596 and A549 cells from β-lap-induced PAR formation (i.e., PARP-1 hyperactivation) (Fig. 4A and B) and attenuated nucleotide depletion (Fig. 4C and D). Thus, PARP-1 inhibition protected cells from β-lap-induced PARP-1 hyperactivation and short-term (48-h TUNEL assays) downstream cell death responses (Fig. 4E). Because 3-AB inhibits PARP-1-dependent DNA repair, long-term survival is preserved. By using NQO₁⁺ breast cancer cells (19), we showed that 1,2-bis(2-aminophenox)-ethane-N,N,N',N'-tetraacetic acid acetoxyethyl ester (BAPTA-AM), a Ca²⁺ chelator, spared cells from β-lap-induced PARP-1 hyperactivation, but allowed repair, enhancing long-term survival (19). Similarly, BAPTA-AM prevented PARP-1 hyperactivation, spared NAD⁺ loss (Fig. 4F and SI Fig. 7), and greatly increased long-term survival in β-lap-treated NQO₁⁺ NSCLC cells (Fig. 4F and SI Fig. 7), highlighting the important role of Ca²⁺-mediated PARP-1 hyperactivation in β-lap-induced cell death.

NQO1 Expression Provides a Unique Therapeutic Window for β-Lap Efficacy in NSCLC Cells. NQO1 is endogenously overexpressed in tumors from NSCLC patients vs. associated normal tissue (Fig. 1A) (15), providing a potential therapeutic window for the use of “bioactivated” compounds, such as β-lap, in the treatment of this disease. Because 2-h β-lap exposures of NQO₁⁺ NSCLC cells were minimally required to irreversibly commit cells to cell death (Fig. 1D and E), we optimized the therapeutic window of this drug. Reports by others (20) suggested that β-lap cytotoxicity in A549 cells was cell cycle and caspase-3 dependent. However, these studies were performed by using continuous administration of β-lap in vitro, a regimen that seemed counterindicated based on our data.

To optimize the therapeutic window of β-lap, we exposed NQO⁺ vs. NQO⁻ NSCLC cells to various doses of β-lap. NQO1-deficient cells (by polymorphism in H596 or in DIC-treated A549 cells) may represent responses of enzyme-deficient cells (e.g., normal tissue) (21). Exposure times of β-lap from 2–8 h were

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optimal to exploit NQO1-H596 or A459 NSCLC cells, while minimally affecting NQO1- cells (Fig. 5). In contrast, longer prolonged exposures (12–24 h) of cells to β-lap abrogated the therapeutic window of this drug in that NQO1- cells were significantly killed by β-lap, presumably through two one-electron oxidoreductions. Responses in A549 cells cotreated with DIC plus β-lap mimicked responses of β-lap-exposed NQO1-H596 NSCLC cells. These data strongly suggest that bolus and not continuous doses of this drug should be efficacious.

Discussion
In numerous animal and cell culture models, NQO1 is elevated/induced in normal tissues/cells in response to low-level carcinogen (22) or ionizing radiation (23) exposures. Importantly, levels of this two-electron oxidoreductase are commonly endogenously elevated 2- to 30-fold in many tumors, including NSCLCs, vs. most human normal tissues (8, 16, 24). Elevated NQO1 levels in NSCLCs were confirmed in our tumor vs. normal lung tissue represent a therapeutically exploitable target for compounds bioactivated by NQO1.

An important consideration in the development of any “NQO1 bioactivatable” compound for NSCLC therapy is that a considerable fraction (10–15%) of tumors from NSCLC patients may contain NQO1 polymorphisms that confer expression loss and drug resistance. Two well characterized NQO1 polymorphisms (NQO1*2, NQO1*3) that inactivate gene expression (25) occur in the human population at reported incidences of 10 and 1%, respectively, (8). Tumors with low or no NQO1 levels in our screen of New York and Hong Kong patient samples (Fig. 1A) are predicted to contain NQO1 polymorphisms.

To examine the mechanism of cell death caused by β-lap in NSCLC, we developed an isogenically matched human NSCLC model system lacking or expressing NQO1 at levels consistent for compounds bioactivated by NQO1.

Fig. 4. Inhibition of PARP-1 hyperactivation delays NQO1-dependent nucleotide pool depletion in NSCLC cells after β-lap. (A and B) NQO1-H596 or A459 cells were pretreated with or without 25 mM 3-AB or mock-treated for 2 h and then exposed to β-lap with or without 3-AB for 20 min. (C and D) NQO1-H596 and A549 cells were treated with β-lap with or without 3-AB as in A, harvested at the indicated times, and analyzed for changes in nucleotide (NAD+/ATP) pool levels as described in Materials and Methods. Results were graphed as means ± SE of experiments performed three times. Student’s t tests were performed. **, P < 0.01 vs. NQO1-H596 cells treated with β-lap alone; A549 cells treated with β-lap plus DIC. (E) A549 cells were mock-treated or pretreated with 3-AB as described (19) and then exposed to β-lap (10 μM, 2 h) and harvested 48 h later. Cells were assessed for apoptosis by TUNEL assays. Student’s t tests were performed. **, P < 0.01 vs. A549 cells treated with β-lap plus 3-AB. (F) Western blot of A549 cells pretreated with 5 μM BAPTA-AM as described in Materials and Methods or mock-treated and then exposed to β-lap (6 μM, 10 min). Samples were then harvested for PAR formation. Survival data are expressed as %T/C. The percentage of NAD+ loss was also monitored as a surrogate for PARP-1 hyperactivation in cells pretreated with 5 μM BAPTA-AM or mock-treated and then exposed to β-lap (6 μM, 1 h). BAPTA-AM-pretreated, β-lap-exposed cells retained NAD+ (87% control), whereas β-lap-treated NQO1- A549 cells lost significant NAD+ levels (43%) measured at 1 h after treatment (see SI Fig. 7B). ND, not determined.
cell death was optimal when short-term drug exposures were administered (2–8 h) in survival assays. Cells with low levels of NQO1 or those treated with DIC, as would be the case for normal tissue, were spared. Indeed, normal lung IMR-90 fibroblasts (SI Fig. 8) that expressed low NQO1 levels were resistant to β-lap, consistent with prior normal cell responses to this drug (21). Importantly, the therapeutic window was eliminated with long-term (>12-h) β-lap exposures. These data suggested that continuous exposure of patients to β-lap should be avoided, and preclinical screening for patients with NQO1 polymorphisms before therapy should be conducted.

The mechanism of cell death induced by β-lap in NSCLC cells (Figs. 1–4) serves to explain and define the compound’s optimal dose-dependent therapeutic window. The metabolism of β-lap by NQO1 results in dramatic ROS formation, extensive DNA damage, and PARP-1 hyperactivation, corroborating our findings in NQO1+ breast cancer cells (19). Excessive DNA damage associated with PARP-1 hyperactivation was noted in ischemia/reperfusion responses in tissues and after conditions (e.g., supraretal doses of H2O2), where extensive DNA single-strand breaks occurred (26, 27). We demonstrated that PARP-1 hyperactivation was a major determinant in NAD+ and ATP loss (Fig. 3), based on kinetics of nucleotide pool loss (i.e., NAD+), and the fact that PARP-1 inhibition by 3-AB (an NAD+ analog) strongly blocked both NAD+ and ATP losses, as well as β-lap-induced lethality. Loss of ATP resulted in Ca2+ influx that ultimately led to μ-calpain activation and atypical cleavage of PARP-1 and p53 (18, 28) (SI Fig. 9). A prior report suggested that caspase activation and cell cycle status were key players in β-lap-induced toxicity in A549 cells (20). However, our data contradict these findings and clearly show that ROS formation, DNA damage, and PARP-1 hyperactivation are critical factors in cell death in NQO1+ NSCLC cells exposed to β-lap regardless of cell cycle status.

When confronted with manageable levels of DNA damage, PARP-1 uses NAD+ as a substrate to add branched and linear poly(ADP-ribose) polymers (Pars) to itself (PAR-PARP-1), as well as other nuclear acceptor proteins, to facilitate DNA break repair. Under normal repair conditions, branched polymers are rapidly degraded by poly(ADP-ribose)glycohydrolase, an exonuclease that does not directly inhibit PARP-1 activity (3, 29, 30). Poly(ADP-ribose)glycohydrolase exerts its effect on PARP-1-mediated toxicity by decreasing PAR turnover, slowing the rate of NAD+ depletion. Using 3-AB, our data suggested that NAD+ depletion was a critical factor in β-lap-induced lethality, significantly delaying ATP loss. Preventing NQO1 activity (Fig. 3) or scavenging ROS upstream (K. F. Reinicke, M.S.B., E.A.B., Y.D., W.G.B., D. R. Spitz, and D.A.B., unpublished data) was far more efficient and significantly inhibited PARP-1 hyperactivation and β-lap lethality. Thus, β-lap exposure causes DNA damage (Fig. 2), and simultaneously inhibits DNA repair by dramatic ATP and NAD+ pool losses. This is a major advantage for β-lap in NSCLC therapy, because very few compounds are efficacious after a short “bolus” administration, and few induce irreversible, cancer-selective lethality regardless of cell cycle status, loss of p53 function, or loss of proapoptotic factors (E.A.B., J. Meng, and D.A.B., unpublished data).

We theorize that β-lap lethality can be further enhanced by using improved drug delivery strategies in combination with a detailed understanding of the drug’s mechanism of action. Our ongoing studies include developing efficacious delivery vehicles [e.g., functionalized micelles, millirod implantable devices (10, 31)], for efficacious delivery of this water-insoluble drug and its potentially more potent prodrugs (32). Future β-lap and NQO1 bioactivated chemotherapies for NSCLC have the potential to play a major role in treating devastating drug resistant cancers, such as NSCLC.

Materials and Methods

Chemicals and Reagents. β-Lap was synthesized by us and dissolved in DMSO (33), 3-AB, DIC, hydrogen peroxide (H2O2), staurosporine, Hoechst dye 33326, BSA, cytchrome c (practical grade), and propidium iodide were purchased from Sigma–Aldrich (St. Louis, MO). BAPTA-AM was purchased from Calbiochem (La Jolla, CA) and dissolved in DMSO. 5-(and-6)-Chloromethyl-2′,7’-dichlorodihydrofluorescein diacetate was purchased from Invitrogen Life Technologies (Eugene, OR).

NQO1 Gene Expression Profiling on Human Lung Cancers by DNA Microarray Analyses. Clinical specimens were obtained from New York and Hong Kong tissue banks containing 30 adenocarcinoma, 11 normal lung tissues (New York), 49 adenocarcinoma, and 9 normal samples (Hong Kong), respectively (SI Tables 1 and 2). mRNA preparation, Affymetrix (Santa Clara, CA) microarray (human U133 plus 2) hybridization, and probe set analyses were performed by using Affymetrix MAS 5.0. The genomic profiling database was maintained by the Lung Cancer SPORE Program at University of Texas Southwestern. NQO1 expression was detected by using two probes (201468_s_at; 210519_s_at), and expression was graphed by histogram (bin size, 1,000 units) using raw data without log transformation (SI Figs. 10.A and C and 11.A and C). Expression was classified as low, high, or higher (SI Tables 1 and 2). Analyses of data using the 201468_s_at probe set was graphed (Fig. 1A).

Tissue Culture. NQO1-deficient H956 NSCLC cells were provided by Su-Shu Pan (University of Pittsburgh, Pittsburgh, PA). A549 cells were generously donated by Steven Dubinett (University of California, Los Angeles, CA). IMR-90 lung fibroblasts were obtained from the American Tissue Type Culture Collection (Manassas, VA). Cells were grown in DMEM with 10% FBS, 2 mM L-glutamine, 100 units/ml penicillin, and 100 mg/ml streptomycin at 37°C in a humidified incubator with a 5% CO2–95% air atmosphere. All cells were mycoplasma free (17, 18).

Generation of Isogenically Matched NQO1-Expressing H596 NSCLC Cells. H596 NSCLC cells are homozygous for the NQO1*2 polymorphism (8), resulting in lack of NQO1 expression/activity (Fig. 1). Log-phase H596 cells were infected with retroviral vectors expressing NQO1 or empty vector, and stable pooled populations, LPC-NQO1 (NQO1+ H596) or LPCX (NQO1− H596), were selected in 1.0 μg/ml puromycin.

NQO1 Assays. Cell lysates were prepared and NQO1 enzyme assays performed with or without DIC (17). Activities were calculated as DIC-inhibited nanomoles of cytochrome c reduced per minute per microgram of protein based on initial rates of OD change at 550 nm and an extinction coefficient for cytochrome c of 21.1 mM/cm (17). Nondetectable NQO1 levels were <1 nmol/min·mg.

Western Blot Analyses. Whole-cell lysates were prepared and proteins were separated by 10% SDS/PAGE (33), α-PARP-1 (sc-8007) and α-p53 (DO-1) antibodies (Santa Cruz Biotechnology, Santa Cruz, CA), as well as α-PAR (BD Pharmingen, San Jose, CA), were used at 1:2,000.

Relative Survival Assays. Long-term, relative survival assays based on DNA content after 7 days of growthposttreatment were performed in 48-well dishes (17). NQ− and NQ+ H596, and A549 cells were treated with or without β-lap at the indicated doses/times, in the presence or absence of 40 or 50 μM DIC. Cells were also pretreated with 5 μM BAPTA-AM (19) before β-lap addition. Results were confirmed by colony-forming ability.
assays (33) and graphed as means ± SE from at least three experiments performed in triplicate.

**ROS Analyses.** Disulffide glutathione and total glutathione levels were assessed (32, 34). Data were expressed as percent disulffide glutathione normalized to protein content measured by Lowry (35). Shown were means ± SE for experiments performed at least three times (SI Fig. 6). ROS formation was confirmed by conversion of nonfluorescent 5-(and 6)-chloromethyl-2′,7′-dichlorodihydrofluorescein diacetate to its fluorescent derivative by flow cytometry (FC-500 flow cytometer; Beckman Coulter Electronics, Miami, FL) (36). Data were graphed as means ± SE for experiments performed three times in duplicate.

**Alkaline Comet Assays.** DNA lesions, including DNA single- and double-strand breaks, were assessed in single cells by using alkaline comet assays from Trevigen (Gaithersburg, MD) (19, 37). Slides were stained with SYBR Green and visualized by using a Nikon (Melville, NY) Eclipse TE2000-E fluorescence microscope. Digital photomicrographs were taken and comet tail lengths were quantified (19).

**Nucleotide Analyses.** Changes in intracellular NAD⁺ levels were measured and intracellular NAD⁺ levels expressed as percent treated divided by control (%T/C) ± SE from at least three individual experiments, each in duplicate (19). In some experiments, cells were pretreated with 5 μM BAPTA-AM or 25 mM 3-AB as described (19). ATP levels were analyzed by using whole-cell extracts by using luciferase-based bioluminescence assays (18). Data were graphed as means ± SE of experiments performed three or more times in triplicate for ATP, or three or more independent experiments for NAD.

**Apoptotic Analyses.** Apoptosis was quantified by using Apo Direct Apoptotic assays (TUNEL) from BD Pharmingen as described (18). Samples were analyzed by using an EPICS Elite ESP or FC-500 flow cytometer (Beckman Coulter Electronics) and Elite acquisition software. Data were expressed as means ± SE from three independent experiments performed in triplicate.

**Statistical Analyses.** Statistical differences were determined by using Student’s t tests, and P values were reported.