NQO1-Mediated Tumor-Selective Lethality and Radiosensitization for Head and Neck Cancer

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Abstract

Ionizing radiation (IR) is a key therapeutic regimen for many head and neck cancers (HNC). However, the 5-year overall survival rate for locally advanced HNCs is approximately 50% and better therapeutic efficacy is needed. NAD(P)H:quinone oxidoreductase 1 (NQO1) is overexpressed in many cancers, and β-lapachone (β-lap), a unique NQO1 bioactivatable drug, exploits this enzyme to release massive reactive oxygen species (ROS) that synergize with IR to kill by programmed necrosis. β-lap represents a novel therapeutic opportunity in HNC leading to tumor-selective lethality that will enhance the efficacy of IR. Immunohistochemical staining and Western blot assays were used to assess the expression levels of NQO1 in HNC cells and tumors. Forty-five percent of endogenous HNCs expressed elevated NQO1 levels. In addition, multiple HNC cell lines and tumors demonstrated elevated levels of NQO1 expression and activity and were tested for anticancer lethality and radiosensitization by β-lap using long-term survival assays. The combination of nontoxic β-lap doses and IR significantly enhanced NQO1-dependent tumor cell lethality, increased ROS, TUNEL-positive cells, DNA damage, NAD+, and ATP consumption, and resulted in significant antitumor efficacy and prolonged survival in two xenograft murine HNC models, demonstrating β-lap radiosensitization of HNCs through a NQO1-dependent mechanism. This translational study offers a potential biomarker-driven strategy using NQO1 expression to select tumors susceptible to β-lap-induced radiosensitization.

Introduction

Head and neck cancer (HNC) is a major cause of morbidity and mortality in the United States with over 40,000 new cases and 8,000 deaths estimated in 2015 (1). If detected early, the majority of HNCs are highly curable using combined modality therapy, where systemic chemotherapy or the antibody cetuximab is administered concurrently with radiation. However, many patients present with high-risk local or regionally advanced disease, and many of these patients will develop either locally recurrent or metastatic disease, conditions for which there are no optimal therapeutic regimens. Moreover, patients that develop locoregional cancer recurrence after receiving standard combined modality therapy have dismal prognoses, even with reirradiation and concurrent chemotherapy (2). Despite the increasing accuracy of radiation dose delivery, it is clear that biologic factors intrinsic to certain tumors confer resistance to therapy (3). Thus, there is great interest in integrating a molecular diagnostic-based approach with targeted therapies for HNC to improve therapeutic efficacy by exploiting tumor-selective targets in combination with radiotherapy.

In multiple tumor histologies, the NAD(P)H:quinone oxidoreductase 1 (NQO1, DT-diaphorase, xip3; E.C.1.6.5.2), is constitutively overexpressed at levels 5- to 200-fold greater in breast, non–small cell lung, pancreas, and prostate cancer compared with associated normal tissues (4–7), and represents a potential therapeutic target. NQO1 is targeted by the unique quinone, β-lapachone (β-lap, 3,4-Dihydro-2,2-dimethyl-2H-naphtho[1,2-b]pyran-5,6-dione) and has antitumor effects in multiple tumor histologies through an NQO1-dependent mechanism (8) involving a futile redox cycling of β-lap by NQO1 between the parental quinone and a reduced hydroquinone, leading to the generation of significant levels of cytotoxic free radical reactive oxygen species (ROS). These ROS, in turn, induce massive DNA base damage, as well as DNA strand breaks, manifesting as predominately single strand breaks (SSB) as well as the much more lethal double strand breaks (DSB) leading to cancer-specific cytotoxicity.
The tumor-selective cytotoxic effects of \( \beta \)-lap occur via an NQO1-dependent \( \mu \)-calpain–mediated, caspase-independent programmed necrosis pathway that selectively kills cancer cells containing high levels of NQO1 compared with adjacent normal tissue (8) resulting in PARP-1 hyperactivation and subsequent cell death (7). These effects occur regardless of cell-cycle status, caspase activity, or functional status of Rb and p53 (9, 10). Of the thousands of quinones known, only \( \beta \)-lap, deoxynoxyquinone (DNQ), and their derivatives, exploit tumor NQO1 expression to cause decreased survival in a wide range of solid cancers (11, 12), resulting in desirable tumor-selective efficacy. Sublethal doses of \( \beta \)-lap can be used with IR to elicit radiosensitization (13, 14) through PARP-1 hyperactivation-induced cytotoxicity in prostate cancer (6). Moreover, \( \beta \)-lap treatment also elicits the release of a large amount of calcium from the endoplasmic reticulum (ER) and preloading cells with BAPTA-AM, a \( \mathrm{Ca}^{2+} \) chelator, or forced ectopic overexpression of Catalase, partially protects NQO1– lung, breast, and pancreatic cancer cell lines from \( \beta \)-lap–induced cell death (11, 15, 16).

The clinically available version of \( \beta \)-lap, ARQ761, is currently in a phase I clinical trial for patients with metastatic solid malignant tumors. Preclinical studies in mice with a similar formulation (\( \beta \)-lap–HP\( \beta \)-CD) demonstrated dose-limiting toxicity due to hemolysis attributed to the carrier, hydroxypropyl-\( \beta \)-cyclodextrin (HP\( \beta \)-CD), and that \( \beta \)-lap–induced methemoglobinemia contributed to the hemolysis noted in vivo (17). Given the ability of low-dose \( \beta \)-lap to radiosensitize NQO1– cancer cells (13, 14), combined modality radiotherapy and low-dose \( \beta \)-lap has the potential to further enhance and extend the tumor-selective cytotoxicity of this agent. These rationale led to our hypothesis that \( \beta \)-lap has the potential to enhance the efficacy of radiotherapy in HNC in an NQO1-dependent fashion.

### Materials and Methods

#### Reagents and chemicals

\( \beta \)-Lap was synthesized and purified by Dr. William Bornmann (7). Dicoumarol (DIC), hydrogen peroxide (\( \mathrm{H}_2\mathrm{O}_2 \)), Hoechst 33342, bovine serum albumin (BSA), cytochrome c, and Catalase were purchased from Sigma-Aldrich. 5-(and -6) chloromethyl-2,7-dichlorodihydrofluorescein diacetate (DCFDA) was purchased from Invitrogen Life Technologies. BAPTA-AM was purchased from Sigma-Aldrich. HP\( \beta \)-lactone (HP\( \beta \)-CD), and that HP\( \beta \)-lactone–CD (HP\( \beta \)-CD) demonstrated dose-limiting toxicity due to hemolysis attributed to the carrier, hydroxypropyl-\( \beta \)-cyclodextrin (HP\( \beta \)-CD), and that HP\( \beta \)-lactone–induced methemoglobinemia contributed to the hemolysis noted in vivo (17). Given the ability of low-dose \( \beta \)-lap to radiosensitize NQO1– cancer cells (13, 14), combined modality radiotherapy and low-dose \( \beta \)-lap has the potential to further enhance and extend the tumor-selective cytotoxicity of this agent. These rationale led to our hypothesis that \( \beta \)-lap has the potential to enhance the efficacy of radiotherapy in HNC in an NQO1-dependent fashion.

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**Cell culture and transfections**

All cell lines were obtained as follows: FaDu, Detroit 562, and CAL-27 cell lines were purchased from ATCC; JHU102 and JHU1022 were provided by Dr. David Sidransky (Johns Hopkins University, Baltimore, MD); SqCC/Y1, Tu-138, MSK-922, TR146, 183, 1483, OSC-19, OSC-19L1, OSC-19L2, OSC-19L3, OSC-19L4, OSC-19LN5, MDA686Ti, MDA686LN, MDA1386TI, MDA1386LN, MDA886LN, MDA1686, HN5, HN30, and HN-31 were provided by Dr. Jeffrey Myers (MD Anderson Cancer Center, Houston, TX); PCI-13, PCI-15A, and PCI-15B were provided by Dr. Theresa Whiteside (University of Pittsburgh Medical Center, Pittsburgh, PA); UM-SCC-1, UM-SCC-10A, UM-SCC-11A, UM-SCC-11B, UM-SCC-14A, UM-SCC-14B, UM-SCC-17A, UM-SCC-17B, UM-SCC-22A, UM-SCC-22B, UM-SCC-25, and UM-SCC-47 were provided by Dr. Thomas Carey (University of Michigan, Ann Arbor, MI). Upon arrival, all cell lines were expanded and aliquots were frozen. Genomic DNA was extracted from one of the aliquots using the DNeasy Blood & Tissue Kit (Qiagen) and sent for genotyping (Powerplex 1.2, Promega). Genotypes were compared against a master list of published HNC genotypes for verification (19), or confirmed as unique against currently available public cell line genotypes. All cell line experiments were conducted using cells with less than 10 passages from the time they were expanded aliquoted and thus all cells used were continuously grown for less than 6 months from the time of genotyping. All cells were cultured in DMEM (Invitrogen) supplemented with 10% FBS as described previously (5), and were verified to be free of mycoplasma. The human shRNA-NQO1 (clone ID: V3LHS_331228) lentivirus vector was purchased from Thermo Scientific and constructed by us. Stable shRNA knockdown clones and scrambled controls were generated as described previously (20). All experiments and cell culture were performed without antibiotics. All cell lines were mycoplasma free.

**NQO1 enzyme assays**

NQO1 enzyme levels (Supplementary Table S1) were determined as previously described (11). Enzyme activities of NQO1 (UI) were calculated as n mole cytochrome c reduced/min/µg protein, based on the initial rate of change in NADH optical density (OD) at 550 nm.

**Relative survival assays**

Relative cell survival levels of HNC cells in vitro were determined by 7-day nuclei counting assay. Briefly, 1–2 × 10³ cells were pretreated into 96-well plates 16 hours before treatment and exposed to \( \beta \)-lap for 2 hours or \( \beta \)-lap combined with Catalase (2,000 UI) or DIC (50 µmol/L) for 2 hours, or pre-treated with the calcium chelator BAPTA-AM (5 µmol/L) for 1 hour and then with \( \beta \)-lap for 2 hours. For combined treatment, cells were exposed to IR followed immediately with sublethal \( \beta \)-lap doses as determined by prior dose titration. After the appropriate incubation times as outlined above, the medium containing the drugs was removed and drug-free medium was then added and cells incubated for an additional 7 days, fixed, and stained with Hoechst 33342. Images of stained nuclei from each treatment were captured using the IN Cell Analyzer 2000 (GE Healthcare) and relative survival was calculated on the basis of cell number. Relative survival based on DNA assays correlated well with colony-forming assays (8). Results were reported as means ± SE from at least three independent experiments performed in triplicate. All cell irradiation was done using the Mark 1 irradiator with a 137Cesium source delivering a dose rate of 3.49 Gy per minute (JL Shepherd & Associates).

**ROS analyses**

ROS formation was quantified after \( \beta \)-lap, or \( \beta \)-lap + IR treatment by staining cells with 5 µmol/L DCFDA as described previously (16), except that analyses were performed using the IN Cell Analyzer 2000. Data were graphed as means ± SE for experiments performed three times, each in triplicate.

**Alkaline comet assays**

DNA strand breaks were assessed using alkaline comet assays as described previously (6, 11; Trevigen). Comet tail lengths were quantified in >100 cells after \( \beta \)-lap exposure using Comet 5.5
software (Andor Technology USA). Experiments were performed three or more times, each in duplicate (7).

**Nucleotide analyses**

Changes in intracellular NAD\(^+\) levels were measured from whole-cell extracts before or after treatment with β-lap, or β-lap + IR using Fluorescent NAD/NADH Detection Kit (Cell Technology). ATP levels were analyzed from whole-cell extracts before or after treatment with β-lap, or β-lap + IR using CellTiter-Glo Luminescent Cell Viability Assays (Promega). ATP levels in mice xenograft tissues were examined using a colorimetric/fluorometric assay according to the manufacturer’s recommended protocol (BioVision). Data were graphed as means ± SE of experiments performed three times in triplicate.

**Flow cytometry**

Terminal deoxyribonucleotidyl transferase–mediated dUTP nick end labeling (TUNEL)-positive cells were quantified using APO-DIRECT assay from BD Pharmingen (BD Biosciences). Samples were analyzed by using a FC-500 flow cytometer (Beckman Coulter, Inc.) as described previously (20, 21). All experiments were repeated at least three times with similar results each time.

**Immunoblot analyses**

Whole-cell extracts and immunoblots were prepared and developed as described previously (20). For immunoblots, primary antibodies (anti-human) and dilutions were: NQO1 (Santa Cruz Biotechnology), 1:5,000; Catalase (Santa Cruz Biotechnology), 1:1,000; PAR (BD Pharmingen), 1:1,000; GAPDH (Santa Cruz Biotechnology), 1:20,000; and β-actin (Santa Cruz Biotechnology), 1:20,000. HRP-conjugated secondary antibodies were purchased from Santa Cruz Biotechnology (1:2,000). Results shown are representative of experiments performed at least three times with similar results each time.

**Immunohistochemical assays**

HNC tissue microarray (TMA) slides were purchased from China (Alenabio). Immunohistochemical staining was performed on 5-μm thick HNC TMA slides via two-step assays as described previously (22). Cytoplasmic and nuclear staining was independently evaluated by two pathologists (Drs. Z.-H. Lin and S. Liu) in a blinded manner. Adjacent sections were stained in the tissue blocks, and many of the tumors did not have adjacent normal tissue companions. Scoring for NQO1 and Catalase staining was graded as follows: no staining or staining observed in less than 10% of tumor cells was given a score 0; faint/barely perceptible staining detected in at least 10% of tumor cells was scored as 1; moderate staining observed in at least 50% of tumor cells scored as 2; strong staining observed in at least 50% of tumor cells was scored as 3. For two-by-two contingency table analysis, 0 and 1 expression levels were grouped as negative and compared with 2 and 3 expression levels which were grouped as positive. In most cases, discrepancies were resolved by re-examination and consensus. DNA DSBs was determined by immunofluorescence of γH2AX foci formation (23). Images were acquired using an Axio Imager 2 microscope (Carl Zeiss) and analyzed using IN Cell Developer Toolbox.
Antitumor efficacy

Head and neck tumors were generated by injecting $1 \times 10^6$ SqCC/Y1 cells into the left neck area of female SCID-NOD mice weighing 20–25 g obtained from the University of Texas Southwestern institutional breeding core. Tumor masses were measured twice per week and mice were stratified so that tumor volumes in each group (5 mice/group) were not statistically different. Four weeks after implantation, mice were treated with HPβ-CD or β-lap-HPβ-CD through tail vein injection as described previously (17), as well as sublethal doses of β-lap-HPβ-CD with or without IR at various doses of Gy, every other day for five treatments. Animals were irradiated using the X-RAD 320 small-animal irradiator (Precision X-Ray). For combination β-lap-HPβ-CD and IR treatments, β-lap-HPβ-CD was administered within 30 minutes after IR. Mice were sacrificed when tumor burdens reached approximately 500 mm$^3$. Survival and tumor volume data were graphed from two separate studies, with 10 combined mice per group. Similar experiments were also repeated using 18–20 g female athymic nu/nu mice (5 mice/group) purchased from Taconic Bioscience. Separately, for pharmacodynamic analyses, SqCC/Y1 tumor-bearing mice were sacrificed 4 hours after various treatments. Tumor tissues were removed and snap-frozen for ATP levels, various treatments. Tumor tissues were removed and snap-frozen for ATP levels, yH2AX foci formation, and histologic examination. All animal studies were carried out under a University of Texas at Southwestern Medical Center Institutional Animal Care and Use Committee approved protocol and in accordance with the guidelines for ethical conduct in the care and use of animals in research.

Statistical analyses

Log-rank tests were applied to Kaplan–Meier survival analyses censored for death. All in vitro statistical analyses were performed using GraphPad Prism software. Statistical analyses of survival data in vivo were performed using linear regression analyses whereby analyses of covariance and nonlinear regression models and overall $P$ values were simultaneously calculated, comparing intercepts and slopes for different treatments. For equitoxic dose calculations, experimental data was fitted using the Carter model with algorithms written in R code and the equitoxic doses listed in Supplementary Table S2 were calculated using the parameters of the Carter model (24). Two-by-two contingency tables using Fisher exact test with a two-tailed $P$ value were used to determine statistical significance in differential expression between negative and positive expression of NQO1 or Catalase in tumor versus adjacent normal tissue using GraphPad QuickCalcS (http://graphpad.com/quickcalcs/contingency1.cfm). Bar graphs were tested for statistical significance using a two-tailed Student t test with SAS (Service Pack 4) for Windows and SigmaPlot. All results were considered to be statistically significant for $P$ values of less than 0.05.

Results

NQO1 is expressed in HNC tissues and cell lines

NQO1 expression and treatment response has been characterized for breast, pancreas, prostate, and lung cancer (4–7). This result prompted the examination of NQO1 from HNC patients using a TMA arrayed with 79 patients (NQO1) and 67 patients (Catalase) from all subsites of the head and neck (Supplementary Table S3). Representative IHC micrographs (Fig. 1A) and the cumulative scoring for each patient is summarized (Fig. 1B). A two-by-two contingency table comparing NQO1 and Catalase expression levels for all patients is shown for NQO1 (Fig. 1C) and Catalase (Fig. 1D). There was a statistically significant difference in the elevated expression levels of NQO1 in tumor compared with adjacent normal tissue and Catalase in adjacent normal tissue compared with tumor. Furthermore, in a separate cohort, increased NQO1 expression correlated with poor overall survival in HNC patients (Supplementary Fig. S1).

As this clinical expression pattern suggests response to β-lap in HNC, we further explored the expression pattern of these two proteins in a large number of HNC cell lines. Representative
Figure 3.

Functional implications of NQO1 expression in response to β-Lap, A, shown are four representative cell lines, including FaDu, SqCC/Y1, and Detroit 562 that express NQO1 and the ‘2 polymorphic UM-SCC-10A that lacks expression (refer to Fig. 2A). Several approaches were taken to demonstrate the role of β-Lap induced NQO1-dependent cell death, including adding the specific NQO1 inhibitor dicoumarol (DIC, 50 μmol/L) or exogenous Catalase (CAT, 2,000 U). β-Lap alone induced significant cell death in a concentration-dependent manner in the three cell lines that expressed NQO1 (β-Lap dose indicated on the x-axis) and cotreatment with DIC completely abrogated cell killing by β-Lap. No cell death was seen in UM-SCC-10A cells after β-Lap exposure. Likewise, cotreatment with exogenous Catalase partially blocked β-Lap-induced NQO1-dependent cell death and had no effect when NQO1 was not expressed (UM-SCC-10A, bottom row). Shown are means ± SE (**, P < 0.001). B, Western blot analyses for NQO1 and Catalase expression in IMR90 primary fibroblasts (left). SqCC/Y1 cells served as positive controls for NQO1 and Catalase expression. GAPDH levels served as a loading control. Relative survival assays in IMR90 primary fibroblasts (right) were performed after treatment with β-Lap alone for 2 hours, with or without DIC (50 μmol/L) or Catalase (2,000 U). β-Lap did not induce any significant cell death at concentrations that produced complete cell death in the cell lines that expressed NQO1 (A). Surpr-high dose β-Lap-induced cell death was abrogated by cotreatment with DIC or Catalase. Shown are means ± SE (**, P < 0.001). All experiments were performed three times in triplicate.

Western blots demonstrated that NQO1 was highly expressed in many of the HNC cell lines (Fig. 2A). The LD50 of β-Lap and NQO1 enzyme activity from IMR90 (closed square) and 41 HNC lines (open squares) were graphed against NQO1 enzyme activities (U), demonstrating a lethality inflection response to β-Lap at around 100 NQO1 U (Fig. 2B). There was no correlation between β-Lap LD50 and NQO1/Catalase ratios (Fig. 2C). These data strongly suggested that NQO1 levels are critical for β-Lap lethality.

HNC cell lines that express NQO1 demonstrate NQO1 activity and response to β-Lap

Cell survival was determined after treating with increasing concentrations of β-Lap in four representative cell lines: FaDu, SqCC/Y1 and Detroit 562 (NQO1 positive), and UM-SCC-10A (NQO1 negative). Cell death was dramatically increased with increasing concentrations of β-Lap through a very sharp inflection point in dose response (Fig. 3A) in FaDu, SqCC/Y1, and Detroit 562, but not in UM-SCC-10A. Cotreatment with the specific NQO1 inhibitor DIC (Fig. 3A) resulted in complete abrogation of β-Lap-induced cell death in NQO1-expressing HNC cell lines. Furthermore, cell survival was partially rescued, requiring higher concentrations of β-Lap for the same effect, in the presence of one-hour pretreatment with BAPTA-AM (Supplementary Table S1) as well as exogenous Catalase (Fig. 3A), supporting a role for the generation of ROS and the release of calcium from the ER in β-Lap–induced NQO1-dependent cell death in HNC. None of these treatments had a significant effect on NQO1-negative UM-SCC-10A cell survival (Fig. 3A, bottom right).

Units of NQO1 activity were determined for a panel of 41 HNC cell lines and IMR90 primary fibroblasts. If NQO1 is expressed, the enzymatic activity (Supplementary Table S1, column 2) and 50% lethal dose of β-Lap (LD50, column 3) is largely a function of NQO1 expression and activity, which can be blocked by DIC (column 4) and above a certain threshold cannot be rescued by Catalase. Cotreatment with BAPTA-AM or exogenous Catalase resulted in an increase in the β-Lap LD50 for a subset of HNC cell lines and IMR90 primary fibroblasts (compare columns 3–5 and 6, respectively).

To further clarify the role of NQO1:Catalase ratio in normal cells, we measured NQO1 enzyme expression and activity as well as Catalase expression in IMR90 primary fibroblast cells and calculated NQO1:Catalase ratios (Fig. 3B). NQO1 enzyme
activity was extremely low (−11 U), and only approximately 20% cell death was noted at 5-fold higher β-lap doses compared with LD50 doses of β-lap required to kill NQO1-expressing HNC lines (Fig. 3A and B), and was significantly rescued by exogenous catalase or DIC. These data support cell death through a NQO1-dependent β-lap redox cycling in NQO1−/− HNC cells due to overwhelming NQO1 activity, which cannot be overcome by tumor cell catalase, and that endogenous catalase activity in normal tissue protects from low levels of NQO1 activity.

Functional consequences of reduced NQO1 expression and mechanisms of β-lap–induced NQO1-dependent cell death

To further clarify the role of the NQO1 enzyme in β-lap–induced NQO1-dependent cell death, shRNA directed against NQO1 was used to stably knockdown NQO1 protein expression (Fig. 4A). Relative survival was then determined for the shRNA scramble control (shSCR) and shRNA-NQO1 knockdown clones #7 and #11. Increasing concentrations of β-lap resulted in much less cell death in the NQO1 knockdown clones compared with the NQO1-intact parental cell line (Fig. 4B and Supplementary Fig. S2).

As β-lap–induced NQO1-dependent cell death has been shown in other cell types to result from the production of ROS that are ultimately converted to H2O2, β-lap–induced oxidative stress in the form of ROS was monitored by DCFDA staining. β-Lap induced a 3-fold increase in ROS formation by 20 minutes, and this effect was completely blocked by DIC in FaDu and SqCC/Y1. H2O2 (500 μmol/L, 15 minutes) served as the positive control and the formation of ROS was unaffected by the presence of DIC (Fig. 4C).

A consequence of increased ROS is localized DNA strand damage, resulting in predominately SSBs as seen by alkaline comet assay. Representative images demonstrated time-dependent increases in the levels of DNA strand breaks with β-lap treatment alone, which was blocked by cotreatment with DIC in SqCC/Y1 and FaDu (Fig. 4D, left and Supplementary Fig. S3A). Comet tail lengths represent the means ± SE from three independent experiments, showing statistically significant differences between β-lap alone or with DIC cotreatment. H2O2 (1 mmol/L, 30 minutes) was used as a positive control and the length of the comet tail was unaffected by the presence of DIC (Fig. 4D, right and Supplementary Fig. S3B).

Dramatic increases in ROS and single-strand DNA breaks can lead to PARP1 upregulation, hyperactivation and high global levels of proteins with poly ADP-ribosylation (PAR) posttranslational modifications. Therefore, cellular PAR levels were determined for total PAR in the presence of 5 μmol/L β-lap without or with DIC cotreatment in FaDu and SqCC/Y1 (Fig. 4E). Representative Western blots demonstrated dramatic increases in PARylation in the presence of β-lap that was significantly blocked by DIC. H2O2 served as a positive control to generate PARylated proteins to confirm the validity of this assay.

As PARP1 hyperactivation results in dramatic losses of ATP and NAD+ in other cell lines (7, 12), ATP and NAD+ levels were examined in response to β-lap in FaDu and SqCC/Y1. Increasing concentrations of β-lap resulted in dramatic reductions in intracellular ATP and NAD+ levels that were completely blocked by cotreatment with DIC (Fig. 4E and Supplementary Fig. S3C).

The mechanism of cell death was further explored using TUNEL to quantify the number of cells with DNA DSBs. The percent of TUNEL-positive FaDu and SqCC/Y1 was elevated with β-lap exposure at the indicated doses and exposure times and abrogated with the cotreatment of DIC (Fig. 4G).

Sublethal doses of β-lap radiosensitize HNC cell lines and result in enhanced ROS formation, DNA DSBs, and loss of ATP when combined with IR

Current administration of β-lap in the clinic requires the carrier HPβ-CD for solubilization and delivery through the blood. However, this combination has the potential to cause methemoglobinemia at high concentrations, which is dose-limiting in preclinical and clinical studies (17, 25). As radiotherapy is used to treat a majority of HNCs, radiosensitization using sublethal doses of β-lap was explored using relative cell survival assays. Consistent with an NQO1-dependent mechanism, the three cell lines FaDu, SqCC/Y1, and Detroit 562 that express NQO1 were radiosensitized by β-lap at concentrations of 1.5 and 2.5 μmol/L, while there was no radiosensitization observed in NQO1-negative UM-SCC-10A (Fig. 5A). Equitoxic doses comparing single with combined treatment of β-lap and IR in HNC cells are listed in values of equivalent doses for FaDu, SqCC/Y1, and Detroit 562 (Supplementary Table S2). Furthermore, increasing doses of β-lap resulted in decreased relative survival in the setting of constant 2 Gy, which was completely blocked by the addition of DIC (Supplementary Fig. S4).

To further explore the mechanistic basis of β-lap–induced radiosensitization, ROS levels at 20 minutes (Fig. 5B) and...
TUNEL+ formation (Fig. 5C) were assessed in SQCC/Y1 after IR in the presence or absence of β-lap. The combination of sublethal doses of β-lap (2.5 μmol/L) + 2 Gy induced significantly increased levels of ROS and TUNEL+ cells compared with either single treatment alone (*, P < 0.05; **, P < 0.01). β-Lap (5 μmol/L, 20 minutes or 2 hours) served as a positive control.

Figure 5.
Combination low-dose radiation and sublethal doses of β-lap result in decreased cell survival and increased ROS, TUNEL positivity, γH2AX foci formation, and ATP consumption. A, relative cell survival assays were performed by treating with β-lap at the specified concentration immediately after IR at the indicated doses for cell lines FaDu, SaCC/Y1, Detroit 562, and UM-SCC-10A. Data represent relative cell survival assays as described in Materials and Methods. B, oxidative stress (ROS, predominately H2O2) was monitored by DCFDA staining and analyzed using high-throughput imaging analysis technology in SaCC/Y1 HNC cells after combined treatment of low-dose IR (Gy) and β-lap (μmol/L) at 20-minute time points. β-lap (5 μmol/L) with or without DIC (50 μmol/L) served as positive and negative controls, respectively. *, P < 0.05, statistically significant differences between β-lap (2.5 μmol/L) + 2 Gy versus β-lap (5 μmol/L) or 2 Gy alone. Cotreatment with DIC (50 μmol/L) rescued the combined treatment induced cell death. Results are means ± SE for studies performed three times. Student t tests were performed to assess for significance (*, P < 0.05; **, P < 0.01). D, representative images of γH2AX foci formation in SaCC/Y1 HNC cells in the presence of increasing doses of β-lap, without or with IR. Quantitation of average γH2AX foci formation demonstrated an increased number of foci at 2 hours in the presence of low dose β-lap (2.5 μmol/L) + 2 Gy or 3 Gy compared with single agents alone. Student t tests were performed to assess statistical significance between identical β-lap concentrations, without or with IR (***, P < 0.001). A lethal dose of β-lap (5 μmol/L), with or without DIC (50 μmol/L) was used as control. E, IR enhanced NAD+ and ATP loss in SaCC/Y1 HNC cells in the presence of sublethal doses of β-lap in a dose-dependent manner for both β-lap with or without IR as indicated. Student t tests were performed comparing β-lap alone and β-lap + IR (*, P < 0.01; **, P < 0.001).
control and ROS and TUNEL \(^+\) cell formation was abrogated by DIC (Fig. 5B and C). As \(\gamma\text{H2AX}\) foci, NAD\(^+\), and ATP depletion play key roles in NQO1-dependent \(\beta\)-lap lethality, we also determined \(\gamma\text{H2AX}\) foci (Fig. 5D), NAD\(^+\), and ATP depletion (Fig. 5E) 2 hours after IR in the presence or absence of \(\beta\)-lap. Shown in Fig. 5D are the representative images of \(\gamma\text{H2AX}\) formation in the presence of increasing concentrations of \(\beta\)-lap, with or without 2 Gy (Fig. 5D) and measured results (Fig. 5D, bar graphs), demonstrating increased numbers of \(\gamma\text{H2AX}\) foci/ nucleus at 2 hours in the presence of \(\beta\)-lap + 2 Gy, compared with mock-irradiated or 2 Gy alone (**, \(P < 0.001\)). A lethal dose of \(\beta\)-lap with or without DIC was used as a positive control for NQO1-dependent formation of \(\gamma\text{H2AX}\) induction. The loss of NAD\(^+\) and ATP following sublethal doses of \(\beta\)-lap in combination with IR was also assessed in SqCC/Y1. IR enhanced loss of NAD\(^+\) and ATP in the presence of sublethal doses of \(\beta\)-lap in a dose-dependent manner for both \(\beta\)-lap and IR (Fig. 5E) with the most pronounced effect at 2.5 \(\mu\)mol/L \(\beta\)-lap and 2 or 3 Gy. Given this unique feature of NAD\(^+\) loss, our data clearly demonstrate the combination of sublethal doses of \(\beta\)-lap and IR kills cancer cells through programmed necrosis.

**Cooperative antitumor efficacy using a combination of \(\beta\)-lap and IR to treat SqCC/Y1 HNC xenograft models**

To further evaluate the role of this combination in a preclinical model, xenografts of HNC were employed. SCID-NOD mice bearing 30 \(\text{mm}^3\) SqCC/Y1 tumor xenografts were treated every other day for five treatments. Tumor volume measurements (Fig. 6A) and Kaplan–Meier overall survival (Fig. 6B) is graphed for control (HP\(\beta\)-CD), \(\beta\)-lap-HP\(\beta\)-CD 10 mg/kg alone, 2 Gy alone, and a combination of 2 Gy plus \(\beta\)-lap-HP\(\beta\)-CD 10 mg/kg. Log-rank analyses were performed comparing survival curves using various IR + \(\beta\)-lap-HP\(\beta\)-CD regimens (**, \(P < 0.001\) for the combined treatment compared with each single treatment). Survival curves show equivalency between HP\(\beta\)-CD and \(\beta\)-lap-HP\(\beta\)-CD 10 mg/kg. C–E, short-term in vivo pharmacodynamic studies to assess \(\gamma\text{H2AX}\) foci formation and ATP levels in SqCC/Y1 HNC xenografts 4 hours after combined treatment with 2 Gy followed by administration of \(\beta\)-lap-HP\(\beta\)-CD as indicated. C, representative micrographs of \(\gamma\text{H2AX}\) foci formation demonstrating a significant increase in foci formation in the combined treatment group compared with all other treatments (D). E, ATP levels are significantly reduced in the combined treatment and not in the control or single treatments (**, \(P < 0.01\)).
was no statistical difference between HPβ-CD (20 mg/kg), β-lap-HPβ-CD (10 mg/kg), or β-lap-HPβ-CD (20 mg/kg) for tumor volume or overall survival in either SCID-NOD or Athymic Nu/Nu mice Scc/Cc-Y1 xenograft models (Supplementary Fig. S5). However, there was a statistically significant difference in tumor volume between β-lap-HPβ-CD (10 mg/kg) + 10 or 20 Gy compared with 10 Gy or 20 Gy alone in the SCID-NOD xenograft model (Supplementary Fig. S5).

Short-term in vivo pharmacodynamic studies were also performed to assess the effects of the different treatments on γH2AX foci formation and ATP consumption in the tumors grown in mice. Xenograft Scc/Cc-Y1 tumors were grown in the necks of mice to 30 mm³ and treated as above. After treatment (4 hours), the tumors were extracted, flash frozen, and assessed for γH2AX foci formation. Representative images are shown (Fig. 6C) and identified a significant increase in γH2AX foci formation in the combination treatment β-lap-HPβ-CD 10 mg/kg and 2 Gy compared with β-lap-HPβ-CD 10 mg/kg alone or 2 Gy alone (Fig. 6D). We also stained Ki-67 in consecutive sections and did not see any significant difference (Supplementary Fig. S6). Furthermore, ATP levels were significantly reduced in the combination arm compared with each modality treatment or vehicle control (Fig. 6E).

Discussion

In this translational study, we present novel data to support a biomarker-driven clinical trial using ARQ761 (β-lap) concurrently with radiotherapy for HNC based upon tumor expression of NQO1 (Fig. 1). NQO1 was significantly elevated in approximately 45% of HNC tissues compared with associated normal tissues with the inverse being true for Catalase. This inverse expression ratio in normal cells provides a favorable microenvironment to exploit the therapeutic window of NQO1 activity in the treatment of HNCs given that Catalase in normal tissue protects against NQO1-dependent β-lap lethality by eliminating bystander ROS (H₂O₂) generated by the β-lap futile cycle (26). In addition, increased NQO1 expression correlated with poor overall survival in HNC patients (Supplementary Fig. S1). Therefore, attacking cancers that express NQO1 utilizing a NQO1 bioactivatable drug that kills through a NQO1-dependent futile redox cycle mechanism presents a theoretically attractive therapeutic target that may overcome previously acquired therapeutic resistance. As NQO1 is also expressed in HNC cell lines (Fig. 2), these data supported further preclinical evaluation of β-lap as a treatment strategy in HNC.

Radiotherapy, often with concurrent chemotherapy, is a central therapeutic modality for the treatment of locally advanced and locoregionally recurrent HNC (27). IR treatment creates a variety of DNA lesions, and if unrepaird, DSBs ultimately result in cell death primarily through mitotic catastrophe. Currently, cisplatin-based chemotherapy is used as standard of care to radiosensitize HNC tumors, but the use of chemotherapy also causes nonspecific normal tissue cytotoxicity, and only cures approximately 50% of patients with locally advanced disease. Therefore, there is a need to identify better tumor radiosensitizers to increase the effectiveness of IR.

The pharmaceutical version of β-lap, ARQ761, is currently in a phase 1 clinical trial for patients with metastatic solid malignancies (www.clinicaltrials.gov), and data generated from this trial will further clarify the optimal dosing for patients, which will be incorporated into the design of a phase 1 clinical trial to assess the safety and toxicity of concurrent β-lap with radiotherapy. Preclinical studies in mice with a similar formulation β-lap-HPβ-CD demonstrated that the maximum tolerated dose (MTD) results from methemoglobinemia toxicity resulting from the carrier agent HPβ-CD, raising concerns that this same phenomenon may also limit human MTD rather than β-lap itself. Therefore, the development of a therapeutic strategy to leverage the tumor-selective cytotoxicity as well as the radiosensitizing capacity of β-lap (13, 14), while reducing exposure to β-lap-HPβ-CD induced side effects through the use of sublethal doses of β-lap, would be highly desirable, and could be done using a combined modality treatment platform with IR.

To test this hypothesis, we combined sublethal doses of β-lap in combination with IR in both cell lines and mouse xenograft studies. For the first time, our data clearly shows the radiosensitizing effects of sublethal doses of β-lap combined with IR in HNC, enhancing the efficacy of IR through the potentiation and accumulation of DNA damage and DSBs as represented by the formation and prolongation of γH2AX foci, as well as the increased consumption of intracellular NAD⁺ and ATP in vitro and in vivo (Figs. 5–6). Combined treatment also resulted in the prolongation of survival and reduced tumor growth without any additional observed cytotoxic effects. The statistically significant difference in tumor growth between 10 or 20 Gy alone and combination therapy β-lap-HPβ-CD 10 mg/kg plus 10 or 20 Gy demonstrated the lack of a durable treatment response with IR alone compared with the combination treatments which is not yet evident in the timeframe of the 20 Gy alone data or survival data of lethal tumor growth (Fig. 6 and Supplementary Fig. S5). These data also support ATP depletion as an important metabolic contributor to the anticancer effects of β-lap combined with IR (11, 12, 28).

Recently, it has been shown that endoplasmic reticulum (ER) stress and calcium flux suppresses DNA DSB repair and sensitizes tumor cells to IR by stimulating proteasomal degradation of Rad51 (29). Other reports suggest that ER stress-induced JNK activation is a critical event to cause mitochondrial apoptosis with β-lap alone or in combination with IR; however, these mechanisms were established with treatment using very high doses of IR (10 Gy) in combination with supratherapeutic doses of β-lap (30) which is not physiologically feasible for current conventional radiotherapy regimens. Thus, the impact of ER stress on the initiation and amplification of DNA damage, as well as DSB repair, after treatment with β-lap and/or β-lap derivatives alone or in combination with IR exposure is still not well understood and we are actively investigating this in HNC models.

In summary, we show for the first time that (i) HNC tumors express NQO1, (ii) normal tissues next to head and neck tumors express catalase, (iii) the cell killing effect of β-lap is dependent on a threshold level of expression and activity of NQO1 in HNC, and (iv) combination sublethal doses of β-lap and IR demonstrate increased efficacy over IR alone in cell lines and in xenograft studies. These data provide compelling evidence to strongly support reduced doses of β-lap as a promising therapeutic partner with IR for the clinical treatment of HNC and extend the application and utility of β-lap-HPβ-CD (ARQ761). This study suggests that HNC samples should be screened for NQO1 expression to identify patients that will likely benefit from combined therapy with β-lap and IR. As such, this study supports the translation of concurrent β-lap and IR treatment into a molecular NQO1 expression biomarker-driven human phase 1 clinical trial for...
high-risk HNC to assess the feasibility of combining radiotherapy with ARQ761.

**Disclosure of Potential Conflicts of Interest**
No potential conflicts of interest were disclosed.

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**Acknowledgments**
The authors thank Dr. Jiming Gao for his helpful suggestions and discussions regarding overall experimental design for these studies.

**Grant Support**
This work was supported using laboratory start-up funds from the UT Southwestern Department of Radiation Oncology (to J.S. Yordy). This work was also supported by NIH grant # R01CA102972 (to D.A. Boothman). The costs of publication of this article were defrayed in part by the payment of page charges. This article must therefore be hereby marked advertisement in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

Received September 16, 2015; revised February 20, 2016; accepted March 14, 2016, published OnlineFirst April 12, 2016.

**References**

Molecular Cancer Therapeutics

NQO1-Mediated Tumor-Selective Lethality and Radiosensitization for Head and Neck Cancer

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