A Correlation between Cytotoxicity and Reductase-Mediated Metabolism in Cell Lines Treated with Doxorubicin and Daunorubicin

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ABSTRACT

The role of metabolism in daunorubicin (DAUN)- and doxorubicin (DOX)-associated toxicity in cancer patients is dependent on whether the parent drugs or major metabolites, daunorubicinol (DOXol) and daunorubicinol (DAUNol), are the more toxic species. Therefore, we examined whether an association exists between cytotoxicity and the metabolism of these drugs in cell lines from nine different tissues. Cytotoxicity studies using MTT [3-(4,5-dimethythiazol-2-yl)-2,5-diphenyl tetrazolium bromide] cell viability assays revealed that four cell lines [HepG2 (liver), HCT-15 (colon), NCI-H460 (lunag), and A-498 (kidney)] were more tolerant to DAUN and DOX than the five remaining cell lines [H9c2 (heart), PC-3 (prostate), OVCAR-4 (ovary), PANC-1 (pancreas), and MCF-7 (breast)], based on significantly higher LC50 values at incubation times of 6, 24, and 48 hours. Each cell line was also assessed for its efficiency at metabolizing DAUN and DOX. The four drug-tolerant cell lines converted DAUN/DOX to DAUNol/DOXol more rapidly than the five drug-sensitive cell lines. We also determined whether exposure to DAUN or DOX induced an increase in metabolic activity among any of these nine different cell types. All nine cell types showed a significant increase in their ability to metabolize DAUN or DOX in response to pre-exposure to the drug. Western blot analyses demonstrated that the increased metabolic activity toward DAUN and DOX correlated with a greater abundance of eight aldo-keto and two carbonyl reductases following exposure to either drug. Overall, our findings indicate an inverse relationship between cytotoxicity and DAUN or DOX metabolism in these nine cell lines.

Introduction

The anthracyclines daunorubicin (DAUN) [(8S,10S)-8-acetyl-10-[(2S,4S,5S,6S)-4-amino-5-hydroxy-6-methylxan-2-yl]oxy-6,8,11-trihydroxy-1-methoxy-5,7,8,9,10,12-hexahydrotetracene-5,12-dione] and doxorubicin (DOX) [(8S,10S)-10-[(2R,4S,5S,6S)-4-amino-5-hydroxy-6-methylxan-2-yl]oxy-6,8,11-trihydroxy-8-(2-hydroxyacetyl)-1-methoxy-5,7,8,9,10,12-hexahydrotetracene-5,12-dione] are two of the most highly effective antineoplastic agents ever developed (Licata et al., 2000; Lakhman et al., 2002; Barry et al., 2007; Deng and Wojnowski, 2007; Menna et al., 2007). Cardiotoxicity appears to have two phases: an acute phase, in which symptoms develop during treatment but are transient; and a latent phase, in which cardiac damage progresses over time, eventually presenting as permanently decreased left ventricular ejection fraction or even CHF (Brouwer et al., 2006). However, there is considerable variability in whether patients develop these cardiomyopathies; some patients are able to tolerate higher, more effective doses without manifesting any cardiac damage. Thus, if the basis of the interpatient sensitivity could be determined, the treatment could be tailored to provide the most effective dose for each patient.

This mechanism(s) that underlie both the antineoplastic and adverse effects of these anticancer drugs are unproven, but may include 1) oxidative stress, including the formation of reactive oxygen species and/or cell membrane damage via lipid peroxidation; 2) intercalation into nucleic acids, causing suppression of DNA, RNA, and protein synthesis; 3) induction of DNA damage through interference with topoisomerase II; and 3) lipid peroxidation; 2) intercalation into nucleic acids, causing suppression of DNA, RNA, and protein synthesis; 3) induction of DNA damage through interference with topoisomerase II;
4) disturbances of calcium balance and iron homeostasis in myocardial release; 5) induction of apoptosis; 6) rise in cardiac histamine release; and 7) generation of toxic metabolites (Klugmann et al., 1986; Gewirtz, 1999; Hrdina et al., 2000; Minotti et al., 2004; Simunek et al., 2009; Mordente et al., 2009; Sawyer et al., 2010). Ample evidence has been published both supporting and countering each of these proposed mechanisms of anthracycline-induced cellular damage; consequently, there is little consensus on the underlying causality of the cellular damage.

Moreover, there is considerable controversy as to whether the parent compound or one of its metabolites is the cytotoxic agent. Some studies suggest that the major metabolites, daunorubicinol (DAUNol) and doxorubicinol (DOXol), are responsible for the adverse effects (Olson et al., 1988; Behnia and Boroujerdi, 1999; Forrest et al., 2000; Olson et al., 2003), whereas others claim that the parent drugs are more toxic (Bernardini et al., 1991; Gonzalez et al., 1995; Ax et al., 2000; Veitch et al., 2009). These studies used a variety of different protocols and biologic systems (different cell lines or animal models) to assess drug-associated toxicity, and the differences among these various methodologies may underlie the disparity in the findings.

In this study, we examined eight human cell lines derived from different tissues and one rat embryonic cardiac cell line to evaluate toxicity of DAUN and DOX or their alcohol metabolites, DAUNol and DOXol. We included a heart cell line because the most serious side effects of anthracycline treatment are chronic cardiomyopathies, such as reduced left ventricular ejection fraction and CHF, and we wished to determine its sensitivity in comparison with other cell types. Our data consistently show that the parent compounds, DOX and DAUN, and not their major metabolites are the primary cytotoxic agents.

Two groups of enzymes have been implicated in the metabolism of DAUN and DOX; these are the aldo-keto reductases (AKRs) and carbonyl reductases (CBRs) (Cummings et al., 1991; Jin and Penning, 2007). We examined the relative abundance and enzymatic activity of eight AKRs and two CBRs in each of the nine cell lines, and found that the degree of cytotoxicity in each cell line is correlated with the activity of these enzymes and their ability to metabolize DAUN and DOX. The cell lines differed in their sensitivity to the drugs, and the heart cell line was among the most sensitive to these anthracycline drugs. Four cell lines were more tolerant to the cytotoxic effects of the parent drug, and this correlated with higher levels of enzyme activity and increased production of the major metabolite. These findings correlated with greater abundance of the AKRs and CBRs within the intracellular fluid of the drug-tolerant cell lines compared with the other five, drug-sensitive, cell lines. Finally, we showed that exposure to either drug results in an increase in AKR and CBR enzyme activity, and this increase in metabolic capacity correlates with an increase in the abundance of these enzymes.

Materials and Methods

Chemicals and Enzymes. DAUN hydrochloride, DOX hydrochloride, dexrazoxane (DEX) [4-[2S]-2-(3,5-dioxopiperazin-1-yl)n-propyl]piperazine-2,6-dione], dimethylsulfoxide, idarubicin hydrochloride (IDA) [\(\text{C}_9\text{H}_8\text{N}_2\text{O}\text{S}\)]-9-acetyl-7-[(2R,4S,5S,6S)-4-amino-5-hydroxy-6-methyloxan-2-yl]oxygen-6,9,11-trihydroxy-5,7,8,9,10,12-hexahydrotetraacene-5,12-dione], 100 × antiobiotic/antimycotic, potassium phosphate (KH\(_2\)PO\(_4\)), 3,4,4,5-dimethyloxazol-2-yl)-2,5-diphenyl tetrazolium bromide (MTT), Temed, sodium chloride (NaCl), sodium monobasic phosphate (Na\(_2\)HPO\(_4\)), Tween 20, and NADPH were purchased from Sigma-Aldrich (St. Louis, MO). DOXol and DAUNol [chemical structures provided in Bains et al. (2008)] were obtained from SynFine Research (Richmond Hill, ON, Canada). High-performance liquid chromatography (HPLC)-grade acetonitrile, ammonium persulfate [(NH\(_4\))\(_2\)S\(_2\)O\(_8\)], formic acid (HCOOH), glycine (NH\(_2\)CH\(_2\)COOH), glycerol [HOCH\(_2\)CH(OH)CH\(_2\)OH], and Tris [NH\(_2\)C(CH\(_2\)OH)\(_3\)] were purchased from Thermo Fisher Scientific (Waltham, MA). Phosphate-buffered saline (PBS; pH 7.4), 100 × antibiotic/antimycotic, and 0.25% trypsin were ordered from Invitrogen Corporation (Carlsbad, CA). Fetal bovine serum albumin and 100 × Protease Arrest were supplied by the American Type Culture Collection (Manassas, VA) and G-Biosciences (Maryland Heights, MO), respectively.

Cell Culture. The OVCAR-4 (ovarian) cell line was kindly provided Dr. Thomas Hamilton (Fox Chase Cancer Center, Jenkintown, PA). The H9c2 rat heart embryonic cell line and HepG2 (liver), NCI-H460 (lung), PAN-1 (pancreatic), A-498 (kidney), MCF-7 (breast), PC-3 (prostate), and HCT-15 (colon) human carcinoma cell lines were obtained from the American Type Culture Collection. HepG2, A-498, and MCF-7 cells were cultured in Eagle’s minimal essential medium. H9c2 and PAN-1 cells were maintained in Dulbecco’s modified Eagle’s medium, whereas the PC-3 cells were cultured with F-12K medium. OVCAR-4, NCI-H460, and HCT-15 cells were maintained in RPMI 1640 medium. All cells were supplemented with 10% fetal bovine serum albumin and 1× antibiotic/antimycotic agent. Cells were grown on BD Falcon cell culture dishes (100 × 20 mm; BD Biosciences, Mississauga, ON, Canada) and maintained in a humidified incubator with 5% CO\(_2\) at 37°C.

MTT Cell Viability Assay to Measure Cytotoxicity. Cells were seeded at densities of approximately 50–60% in Nunclon 48-well cell culture plates (Thermo Fisher Scientific) and were allowed to attach overnight in a humidified incubator with 5% CO\(_2\) at 37°C. The next day, cells were treated with varying concentrations of DAUN or DOX (0, 0.01, 0.025, 0.05, 0.1, 0.25, 0.5, 1, 2, 5, 10, 25, 50, 100, and 150 \(\mu\)M) for specified time periods (0, 6, 24, or 48 hours). After treatment for each of the time periods, MTT solution (5 mg/ml in PBS; pH 7.4) was added (62.5 \(\mu\)l/well), and the plates were incubated for another 4 hours at 37°C. Living cells are able to reduce MTT to an insoluble, colored (dark purple) formazan product by mitochondrial succinate dehydrogenase, while dead cells cannot. Following the 4-hour incubation period, cells were harvested and solubilized by dimethylsulfoxide, and absorbance values of the formazan product were measured at 570 nm (37°C) using a monochromator-based Synergy M\(_2\) multimode microplate reader with ultra-fine-tuned performance using a Gen5 version 1.08.4 software (BioTek Instruments, Inc., Winooski, VT). Vehicle-treated cells (water without drug) were used as controls. For each cell line exposed to DAUN or DOX at each time interval, MTT assays were performed in three independent experiments and repeated in triplicate. The percentage of live cells was calculated relative to the control wells using the following equation: [(Absorbance value of experimental well)/(Absorbance value of control well)] × 100. These percentage values were used to construct LC\(_{50}\) dose-response curves with the GraphPad Prism version 4.0 program (GraphPad Software Inc., La Jolla, CA). LC\(_{50}\) values for each cell line were determined following DAUN and DOX exposure at each concentration of the drug and at the aforementioned time intervals. MTT assays were repeated again to determine LC\(_{50}\) values in all cell lines for the 48-hour exposure period with the major metabolites, DAUNol and DOXol (0, 0.5, 1, 5, 10, 25, 50, 100, 250, 500, 1000, 1500, 2000, and 3000 \(\mu\)M).

Permeability Assays to Quantify Extra- and Intracellular Anthracycline Levels. Permeability studies were done to determine whether there were differences among the nine cell types in their ability to absorb or export either the parent drug or its primary
metabolite. For this set of experiments, cells were grown in BD Falcon cell culture dishes (35 mm × 10 mm) and maintained in a humidified incubator with 5% CO2 at 37°C in their respective growth media until they achieved a cell density of 50%. Media was aspirated the following day and replaced with 4 ml media with a final concentration of 1 μM DOX or DOXol. With respect to anthracyclines such as DOX and DAUN, 1 μM represents human physiologic concentration (Hempel et al., 2002; Liu et al., 2008; Hanna et al., 2011). For each cell line, different culture dishes were set up for incubation at 0 minutes, 20 minutes, 1 hour, 3 hours, 6 hours, and 24 hours. After the incubation time period, the media (representing the extracellular portion) were collected and retained for further analyses. The cells were then washed twice with PBS (4-ml volume per wash) and collected in 0.5 ml of PBS using a scraper; they were then lysed by sonication and centrifuged at 10,000g for 10 minutes at 4°C to obtain the supernatant fraction containing the intracellular fluid (cytosol and nuclear fluid) while the pellet fraction containing cellular debris and genomic DNA was discarded.

The media collected from the permeability assays were diluted 15-fold in the same culture media to a final volume of 150 μl and placed in 1.5-ml Eppendorf tubes. The intracellular samples were also diluted 15-fold to a final volume of 150 μl, except that the dilution was in PBS. To each of the tubes, 300 μl of ice-cold acetonitrile was added, which contained 0.4 μg/ml IDA as an internal standard. The media and intracellular samples were then subjected to vortex mixing and centrifuged at 10,000g for 10 minutes at 4°C to remove protein. The supernatants were removed for each sample, and quantification of DOX and DOXol was achieved using liquid chromatography–tandem mass spectrometry (LC/MS/MS).

DAUN and DOX In Vitro Metabolic Assays. Intracellular fluid (cytosol and nuclear fluid) from the rat heart and human carcinoma cell lines was extracted according to the protocol provided for mammalian cells by QIAGEN Inc. (Mississauga, ON, Canada). Cells were washed in PBS, collected for 5 minutes at 1000g, resuspended in lysis buffer (50 mM NaH2PO4, 300 mM NaCl; pH 8.0) with 0.05% Tween 20, and lysed by sonication. The lysate was centrifuged at 10,000g for 10 minutes at 4°C to pellet cellular debris and genomic DNA. A final concentration of 1 x ProteaseArrest was added to the supernatant to prevent protein degradation, and the supernatant was stored for 20% glycerol at −20°C.

The enzymatic conversion of DAUN and DOX to their respective major metabolites, DAUNol and DOXol, was measured in intracellular fluid collected from cell lines. Assays were performed in 1.5-ml Eppendorf tubes, closely resembling the Kassner et al. (2008) study: 20–30 μg total intracellular fluid protein, 1 μM DAUN or DOX substrate, 2 mM NADPH, 100 mM KH2PO4; pH 7.4 at 37°C, 30 minutes at 250 rpm. A vehicle control (water) was also run in conjunction with the metabolic assays. The total volume for each assay was 150 μl.

Effect of DEX on DOX Metabolism. Sometimes DEX is incorporated with anthracyclines as a potential cardioprotective agent during cancer treatment (Wouters et al., 2005; Choi et al., 2010). Therefore, another set of metabolic assays was performed with the addition of DEX to determine whether it significantly altered the metabolic conversion of anthracyclines to their major metabolites. In North America, DEX is administered at 10-fold the DOX dose (10:1 ratio); therefore, 10 μM was chosen as a final concentration in the metabolic assays (Plandé et al., 2006). A vehicle control (water), along with a DEX-only control (no DOX present), was performed in conjunction with the aforementioned metabolic assays.

Intracellular fluid protein concentrations used in the metabolic studies were determined using the Bradford protein assay with bovine serum albumin as a standard. The enzymatic reaction was stopped by adding 300 μl of ice-cold acetonitrile, which contained 0.4 μg/ml IDA, followed by vortex mixing and centrifuging at 10,000g for 10 minutes at 4°C to remove protein. The supernatant was removed, and quantification of the DAUNol and DOXol metabolites was achieved using LC/MS/MS.

Instrumentation and Experimental Conditions for LC/MS/MS. The LC/MS/MS analytical method is based on a previously reported assay with modifications to the chromatography, sample preparation, and detection (Lachâtre et al., 2000). The metabolic assays were analyzed using an ultra performance liquid chromatography–tandem mass spectrometry (UPLC/MS/MS) system, which consisted of a Waters Acquity ultra performance liquid chromatograph (UPLC) connected to a Waters Quattro Premier XE triple-quadrupole mass spectrometer using an electrospray ionization source (Waters Corporation, Milford, MA). Chromatographic separation of DOX, DOXol, DAUN, DAUNol, and IDA (internal standard) was performed using a Waters Acquity UPLC bridged ethyl hybrid C18 column (100 mm × 2.1 mm i.d., 1.7-μm particle size) with the following mobile phase composition and gradient programming: water with 0.1% formic acid (A), acetonitrile with 0.1% formic acid (B); 0 minutes, 5% B; 1 minute, 5%; 2 minutes, 98% B; 4 minutes, 98% B; 4.1 minutes, 5%; and 6 minutes, 5% B. The flow rate was maintained at 0.2 ml/min with a total run time of 6 minutes. The mobile phase flow was diverted to waste before 2.5 minutes and after 3.5 minutes during the chromatographic run. The mass spectrometer was operated in positive ionization mode with a capillary voltage of 3.5 kV, cone voltage of 40 V, and desolvation temperature of 300°C. The analytes were detected in multiple reaction monitoring mode using the total ion current of the following ion transitions and collision energy (CE) values (in eV): for DOX, m/z 544.1 → 361.2 (CE, 20), m/z 544.1 → 379.0 (CE, 20), and m/z 544.1 → 397.2 (CE, 10); for DOXol, m/z 546.0 → 345.0 (CE, 35), m/z 546.0 → 363.1 (CE, 20), and m/z 546.0 → 398.9 (CE, 10); for DAUN, m/z 527.9 → 321.0 (CE, 20), m/z 527.9 → 363.2 (CE, 20), and m/z 527.9 → 381.0 (CE, 10); for DAUNol, m/z 530.1 → 362.6 (CE, 35), m/z 530.1 → 382.1 (CE, 20), and m/z 530.1 → 383.1 (CE, 10); and for IDA, m/z 497.9 → 291.2 (CE, 25), m/z 497.9 → 333.0 (CE, 25). Data were acquired and processed using the MassLynx version 4.1 software (Waters Corporation). The limit of quantitation for DOXol and DAUNol was 4.58 nM and 4.42 nM, respectively. Accuracy and precision met the acceptance criteria of <15% bias from the theoretical concentration and <15% coefficient of variation for calculated concentrations with six replicate samples prepared at three quality control levels within the range of the method.

For the permeability assay analyses, the UPLC/MS/MS method was transferred to an ultra high performance liquid chromatography–tandem mass spectrometry (UHPLC/MS/MS) system, and DOXol was quantified using this instrumentation. The UHPLC/MS/MS system consisted of an Agilent 1290 Infinity Binary Pump, an Agilent 1290 Infinity Thermostated Column Compartment (Agilent Technologies, Santa Clara, CA) connected to an AB Sciex QTRAP 5500 hybrid linear ion trap triple-quadrupole mass spectrometer equipped with a TurbolonSpray ionization probe. Chromatographic separation of DOX, DOXol, and IDA was achieved using the same column, mobile phase composition, and flow rate as for the UPLC/MS/MS system, and the gradient programming was slightly modified as follows: 0 minutes, 10% B; 0.5 minute, 10% B; 4 minutes, 90% B; 5 minutes, 90% B; 5.1 minutes, 10% B; and 7 minutes, 10% B. The total run time was 7 minutes, and the mobile phase flow was diverted to waste before 3.0 minutes and after 5.0 minutes during the chromatographic run.

The QTRAP 5500 mass spectrometer was operated in positive ionization mode with a curtain gas flow of 30 units, ion spray voltage of 5500 V, TurbolonSpray temperature of 300°C, and collision-activated dissociation set high. DOX, DOXol, and IDA were detected in multiple reaction monitoring mode, at unit resolution, using similar ion transitions as described for the UPLC/MS/MS method. Data were acquired and processed using the Analyst version 1.5.2 software (AB Sciex LP). The UHPLC method was qualified for the quantification of DOX and DOXol. The limits of quantification for DOX and DOXol were improved to 1.72 nM and 1.83 nM, respectively. Accuracy and precision met the acceptance criteria of not more than
16% bias from the theoretical concentration and not more than 12% coefficient of variation for calculated concentrations with four replicate samples prepared at three quality control levels within the range of the method.

Western Blotting of Intracellular Fluid from Cell Lines to Detect AKRs and CBRs. Western blot analyses of the intracellular fluid extracted from each cell line were conducted according to the manufacturer’s instructions for the Odyssey (LI-COR Biosciences, Lincoln, NE). Following 18% SDS-PAGE, intracellular proteins were transferred at 20 V in Towbin’s buffer (25 mM Tris, 192 mM glycine, and 20% [v/v] methanol) overnight (at 4°C) to a Hybond-C Extra nitrocellulose membrane (GE Healthcare, Piscataway, NJ). The membranes were blocked in Odyssey blocking buffer, and the enzyme was detected using a MaxiPab polyclonal mouse anti-human AKR1A1, AKR1B1, AKR1B10, AKR1C1, AKR1C2, AKR1C3, AKR1C4, AKR7A2, CBR1, or CBR3 antibody (Abnova Corporation, Taipei City, Taiwan) (diluted 1:2500) as the primary antibody and IRDye 800CW goat anti-mouse IgG as the secondary antibody (diluted 1:5000) (LI-COR).

Previous studies suggest that the reductase enzymes metabolize DAUN and/or DOX; hence, they were selected for this study (Ohara et al., 1995; O’Connor et al., 1999; Martin et al., 2006; Bains et al., 2008, 2009, 2010a; Kassner et al., 2008). Both primary and secondary antibodies were in blocking buffer containing 0.1% Tween 20. The bound secondary antibody was detected using the Odyssey Infrared Imaging system (LI-COR). β-Tubulin served as a loading control and was detected using the same protocol, except that a mouse monoclonal anti-β-tubulin primary antibody (Abcam Inc., Cambridge, MA) was used (diluted 1:1000). Band intensities for AKR or CBR proteins were determined using Odyssey densitometry software and were normalized to band intensities of β-tubulin to quantify the relative expression of the individual reductases in each intracellular fluid extract.

Induction of AKR and CBR Expression in Cell Lines Exposed to Anthracycline Drugs. All of the cell lines were pretreated with 100 nM DAUN or DOX for 0, 6, 24, or 48 hours. This drug concentration was selected because cell viability was ≥75% based on the dose-response curves generated from the cytotoxicity study. For analysis at each time interval, the cells were washed three times with PBS, and intracellular fluid extracts were prepared and tested for their ability to metabolize DAUN or DOX to their respective major metabolites, DAUNol and DOXol. The in vitro metabolic assays were conducted as described above using either 1 μM DAUN or 1 μM DOX as substrates.

We performed Western blots on intracellular fluid extracts from cells exposed to DOX and DAUN to determine whether increases in drug metabolic activity correlated with increased expression (protein levels) of some or all of the AKRs and CBRs analyzed in this study. The relative abundance of each of the reductase enzymes in each intracellular fluid extract was determined as described above.

Statistical Analysis. Statistical analyses were performed using GraphPad Instat (version 3.6; GraphPad Software Inc.). Percent viabilities used to create dose-response curves from the cytotoxicity assays were expressed as means ± S.D., while LC50 values were provided along with the 95% confidence intervals. Results from the permeability/metabolic assays and reductase expression studies were reported as means ± S.D. and compared using one-way analysis of variance followed by Tukey-Kramer multiple comparisons tests. Differences were considered significant at P < 0.05.

Results

Anthracycline Cytotoxicity. The cytotoxicity of the anticancer drugs DAUN, DOX, and their metabolites (DAUNol and DOXol) was determined in nine different cell types using the MTT assay. Cell viability was measured after incubating each cell line with various concentrations of the anthracycline parent drug or its major alcohol metabolite for 0 (100% viable), 6, 24, or 48 hours. Dose-response curves were plotted for all nine cell lines; two representative plots are presented in Supplemental Fig. 1. The LC50 values for all nine cell types were calculated from these curves and are provided in Table 1 (for DAUN and DAUNol) and Table 2 (for DOX and DOXol).

Three observations are worth mentioning from these data sets. First, the nine cell types were easily grouped into two categories. Four cell lines, HepG2 (liver), HCT-15 (colon), NCI-H460 (lung), and A-498 (kidney), were found to be more tolerant to DAUN and DOX (hereafter called the drug-tolerant group) compared with the five remaining cell lines, H9c2 (heart), PC-3 (prostate), OVCAR-4 (ovary), PANC-1 (pancreas), and MCF-7 (breast) (hereafter called the drug-sensitive group). This finding was consistent for all time points examined and was statistically significant in all cases. Second, DOX was significantly more toxic than DAUN for each of the cell lines tested. Third, in all nine cell types, DAUNol and DOXol were significantly less toxic than their respective parent drug. Indeed, the DAUNol LC50 values were 30- to 108-fold greater than those for DAUN, while the DOXol LC50 values were 59- to 162-fold greater than those for DOX. Taken together, the simplest interpretation of these findings

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\text{Table 1}
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Mean LC50 values of DAUN and DAUNol for cell lines at specified time intervals following exposure to the drug.

<table>
<thead>
<tr>
<th>Cell Line</th>
<th>DAUN (μM)</th>
<th>DAUNol (μM)</th>
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<tbody>
<tr>
<td>H9c2 (heart)</td>
<td>12.6 (11.2–14.1)</td>
<td>3.2 (3.0–3.5)</td>
</tr>
<tr>
<td>PC-3 (prostate)</td>
<td>10.2 (9.2–11.4)</td>
<td>3.2 (2.9–3.6)</td>
</tr>
<tr>
<td>OVCAR-4 (ovary)</td>
<td>11.1 (9.8–12.5)</td>
<td>3.1 (2.8–3.4)</td>
</tr>
<tr>
<td>PANC-1 (pancreas)</td>
<td>11.4 (10.1–13.0)</td>
<td>3.6 (3.2–4.0)</td>
</tr>
<tr>
<td>MCF-7 (breast)</td>
<td>14.1 (11.1–19.6)</td>
<td>4.2 (3.8–4.6)</td>
</tr>
<tr>
<td>HepG2 (liver)</td>
<td>21.5 (18.4–25.1)</td>
<td>9.5 (8.3–10.9)</td>
</tr>
<tr>
<td>HCT-15 (colon)</td>
<td>19.7 (17.0–23.7)</td>
<td>9.9 (8.7–11.3)</td>
</tr>
<tr>
<td>NCI-H460 (lung)</td>
<td>21.0 (18.1–24.3)</td>
<td>10.3 (9.3–11.5)</td>
</tr>
<tr>
<td>A-498 (kidney)</td>
<td>22.9 (20.5–25.6)</td>
<td>13.7 (12.4–15.0)</td>
</tr>
</tbody>
</table>
Either DOX or DOXol for periods of 20 minutes, 1 hour, 3 hours, 6 hours, and 12 hours. Each cell line was exposed to and Hct-15) and drug-sensitive (H9c2, PANC-1, and MCF-7) groups was used in these assays. Each cell line was exposed to between the drug-tolerant and drug-sensitive cell types. A causes in rate of drug or metabolite uptake and/or efflux were performed permeability assays to determine whether differ- nces in rate of drug or metabolite uptake and/or efflux were associated with the substantial difference in LC50 values. The first five entries of the table refer to the sensitive cell lines and the last four entries to the tolerant cell lines.

Permeability of Cell Lines to DOX and DOXol. We performed permeability assays to determine whether differences in rate of drug or metabolite uptake and/or efflux were associated with the substantial difference in LC50 values between the drug-tolerant and drug-sensitive cell types. A subset of the cell lines from the drug-tolerant (HepG2, A-498, and Hct-15) and drug-sensitive (H9c2, PANC-1, and MCF-7) groups was used in these assays. Each cell line was exposed to either DOX or DOXol for periods of 20 minutes, 1 hour, 3 hours, 6 hours, and 24 hours. After the treatment period, the media and cells were separated as described (see Materials and Methods), and the amounts of extracellular (in media) and intracellular (cytosolic and nuclear fluid) parent drug and its major metabolite were determined.

Four observations can be made from the permeability studies. First, during the 24-hour incubation period, cell lines exposed to 1 μM DOX exhibited significantly greater intracellular DOX levels (Table 3) compared with intracellular DOXol levels from the same cell lines exposed to 1 μM DOXol (Table 4). Although DOX and DOXol are structurally similar, the difference in the hydroxyl group on carbon-13 of DOXol likely hinders its influx compared with DOX. Second, the intracellular levels of DOXol were nearly identical regardless of whether the cells were exposed to 1 μM DOX or DOXol during the treatment periods (compare Tables 4 and 5). Therefore, it is unlikely that the accumulation of the major metabolite, DOXol, plays a significant role in anthracycline-associated cytotoxicity. Third, following 24 hours of exposure to DOX, the amount of intracellular DOXol (Table 5) was significantly greater among the drug-tolerant cell lines (kidney, colon, and liver) than it was among the drug-sensitive cell lines (heart, pancreas, and breast). This observation, along with the observation that the intracellular levels of DOX were significantly higher among the drug-sensitive cells than among the drug-tolerant cells (Table 3), suggests that

TABLE 3
Anthracycline levels from permeability assays using three cell lines from both the drug-sensitive and the drug-tolerant groups (sensitive: H9c2, PANC-1, and MCF-7; tolerant: A-498, HCT-15, and HepG2) treated with 1 μM parent drug (DOX) or major metabolite (DOXol) at intervals of 20, 60, 180, 360 and 1440 minutes.

Intracellular DOX levels after treatment with DOX. DOX and DOXol levels are reported as mean ± S.D. (n = 3).

<table>
<thead>
<tr>
<th>Time</th>
<th>H9c2 (Heart)</th>
<th>PANC-1 (Pancreas)</th>
<th>MCF-7 (Breast)</th>
<th>A-498 (Kidney)</th>
<th>HCT-15 (Colon)</th>
<th>HepG2 (Liver)</th>
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<tbody>
<tr>
<td>20 min</td>
<td>122 ± 13</td>
<td>105 ± 9</td>
<td>155 ± 19</td>
<td>112 ± 11</td>
<td>137 ± 9</td>
<td>119 ± 9</td>
</tr>
<tr>
<td>60 min</td>
<td>197 ± 18</td>
<td>182 ± 15</td>
<td>283 ± 18</td>
<td>186 ± 12</td>
<td>174 ± 10</td>
<td>144 ± 10</td>
</tr>
<tr>
<td>180 min</td>
<td>420 ± 30*</td>
<td>316 ± 29</td>
<td>384 ± 14*</td>
<td>299 ± 18</td>
<td>250 ± 17</td>
<td>277 ± 19</td>
</tr>
<tr>
<td>360 min</td>
<td>569 ± 31*</td>
<td>467 ± 40</td>
<td>585 ± 25*</td>
<td>440 ± 33</td>
<td>409 ± 27</td>
<td>395 ± 29</td>
</tr>
<tr>
<td>1440 min</td>
<td>748 ± 38*</td>
<td>683 ± 25*</td>
<td>783 ± 45*</td>
<td>583 ± 35</td>
<td>530 ± 39</td>
<td>588 ± 23</td>
</tr>
</tbody>
</table>

*P < 0.05, denotes a value significantly different from all three drug-tolerant cell lines.
*P < 0.05, denotes a value significantly different from the heart cell line.
*P < 0.05, denotes a value significantly different from the pancreas cell line.
both cell types are capable of taking up DOX, perhaps at relatively comparable rates, but that the drug-tolerant cells convert DOX to DOXol at a higher rate. Indeed, this correlates with the findings from the metabolic studies (see below). Moreover, the extracellular levels of DOXol were at least 3-fold higher than the intracellular levels in the cells treated with the parent drug (compare Tables 5 and 6), which suggests that all of the cells are able to export the metabolite and the amount exported correlates with the amount generated. Fourth, the extracellular levels of DOX found in the three drug-tolerant cell lines and the three drug-sensitive cell lines were not significantly different from each other after 20 minutes of exposure to DOX (Table 3). However, after 24 hours of exposure, the amount of intracellular DOX in the three drug-sensitive cell lines was significantly higher than that found in the three drug-tolerant cell lines. Taken together, these data suggest that the drug-tolerant cell lines convert DOX to DOXol more rapidly than the drug-sensitive cell lines. The alternative hypothesis, that the drug-tolerant cell lines take up DOX less efficiently, seems less likely since after a 20-minute exposure period both cell types have taken up nearly identical amounts of DOX, and transport of the anthracyclines is by passive diffusion of the nonionized free base, which is in equilibrium with the ionized drug (Skovsgaard and Nissen, 1982; Sparreboom et al., 2002).

In summary, the most parsimonious interpretations of these data are that the cell types do not show any notable differences in influx of the drug or efflux of its primary metabolite. The data suggest that the drug-tolerant cell lines metabolize DOX at higher rates than the drug-sensitive cell lines. 

In Vitro Metabolic Assays and Western Blot Analyses of Cell Lines. If the drug-tolerant group of cell types does metabolize DOX and DAUN more efficiently than the cell lines comprising the drug-sensitive group, then one would predict that they would have higher levels of the enzymes that metabolize these anthracyclines. Therefore, we 1) measured the amount of eight AKRs and two CBRs in each of the cell lines and 2) performed in vitro metabolic assays using cell line intracellular fluids with either DOX or DAUN as substrate and asked whether metabolic conversion of the drug to its metabolite is correlated with the enzyme levels and if either or both of these parameters correlate with the sensitivity of each cell type to these anthracycline drugs.

Among the five cell lines that comprise the drug-sensitive group (H9c2, PC-3, OVCAR-4, PANC-1, and MCF-7), the rates of conversion of DAUN to DAUNol ranged from 17.6 ± 1.0 to 50.0 ± 8.6 pmol of DAUNol/min-mg intracellular fluid protein and the rate of conversion of DOX to DOXol ranged from 1.0 to 5.0 ± 0.8 pmol of DOXol/min-mg intracellular fluid protein (Fig. 1). The four cell lines that comprise the drug-tolerant group (HepG2, HCT-15, NCI-H460, and A-498) had significantly higher metabolic rates, ranging from 50.0 ± 3.2 to 80.7 ± 9.7 pmol of DAUNol/min-mg and 9.3 ± 0.8 to 10.5 ± 1.1 pmol of DOXol/min-mg (Fig. 1). As a result, the five drug-sensitive cell lines were classified as “slow metabolizers” and

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**TABLE 4**

Anthracycline levels from permeability assays using three cell lines from both the drug-sensitive and the drug-tolerant groups (sensitive: H9c2, PANC-1, and MCF-7; tolerant: A-498, HCT-15, and HepG2) treated with 1 μM parent drug (DOX) or major metabolite (DOXol) at intervals of 20, 60, 180, 360 and 1440 minutes

<table>
<thead>
<tr>
<th>Time</th>
<th>H9c2 (Heart)</th>
<th>PANC-1 (Pancreas)</th>
<th>MCF-7 (Breast)</th>
<th>A-498 (Kidney)</th>
<th>HCT-15 (Colon)</th>
<th>HepG2 (Liver)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 min</td>
<td>4 ± 1</td>
<td>6 ± 1</td>
<td>6 ± 1</td>
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<tr>
<td>60 min</td>
<td>8 ± 1</td>
<td>11 ± 2</td>
<td>14 ± 2</td>
<td>13 ± 2</td>
<td>13 ± 1</td>
<td>14 ± 2</td>
</tr>
<tr>
<td>180 min</td>
<td>16 ± 2</td>
<td>21 ± 3</td>
<td>22 ± 2</td>
<td>21 ± 2</td>
<td>26 ± 2</td>
<td>37 ± 3</td>
</tr>
<tr>
<td>360 min</td>
<td>23 ± 3</td>
<td>29 ± 4</td>
<td>39 ± 3</td>
<td>42 ± 3</td>
<td>37 ± 3</td>
<td>61 ± 4</td>
</tr>
<tr>
<td>1440 min</td>
<td>42 ± 8</td>
<td>53 ± 3</td>
<td>51 ± 2</td>
<td>65 ± 3</td>
<td>69 ± 4</td>
<td>66 ± 3</td>
</tr>
</tbody>
</table>

*P < 0.05, denotes a value significantly different from the heart cell line.

**TABLE 5**

Anthracycline levels from permeability assays using three cell lines from both the drug-sensitive and the drug-tolerant groups (sensitive: H9c2, PANC-1, and MCF-7; tolerant: A-498, HCT-15, and HepG2) treated with 1 μM parent drug (DOX) or major metabolite (DOXol) at intervals of 20, 60, 180, 360 and 1440 minutes

<table>
<thead>
<tr>
<th>Time</th>
<th>H9c2 (Heart)</th>
<th>PANC-1 (Pancreas)</th>
<th>MCF-7 (Breast)</th>
<th>A-498 (Kidney)</th>
<th>HCT-15 (Colon)</th>
<th>HepG2 (Liver)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 min</td>
<td>4 ± 1</td>
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<td>5 ± 1</td>
<td>9 ± 2</td>
<td>7 ± 2</td>
<td>9 ± 1</td>
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<td>10 ± 1</td>
<td>17 ± 3</td>
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<td>360 min</td>
<td>29 ± 3</td>
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<td>33 ± 3</td>
<td>50 ± 5</td>
<td>45 ± 3</td>
<td>49 ± 4</td>
</tr>
<tr>
<td>1440 min</td>
<td>48 ± 3</td>
<td>43 ± 5</td>
<td>53 ± 3</td>
<td>71 ± 5</td>
<td>67 ± 4</td>
<td>71 ± 4</td>
</tr>
</tbody>
</table>

*P < 0.05, denotes a value significantly different from the heart cell line.

*P < 0.05, denotes a value significantly different from the pancreas cell line.

*P < 0.05, denotes a value significantly different from all three drug-sensitive cell lines.
the four drug-tolerant cell lines as “rapid metabolizers” of these anthracyclines. In addition, all cell lines were shown to metabolize DAUN more rapidly than DOX.

Western blot analysis of intracellular fluid fractions revealed that each of the rapid-metabolizer cell lines express the eight AKRs and two CBRs at significantly higher levels than any of the slow-metabolizer cell lines (Fig. 2). Distinct bands with electrophoretic mobilities corresponding to the calculated molecular mass for each of the enzymes, 35–38 kDa for the AKRs and 30 kDa for the CBRs, were detected in each extract (Supplemental Fig. 2). These data suggest that the difference between the rapid- and slow-metabolizing cell types in their rates of conversion of DAUN/DOX to DAUNol/DOXol in the in vitro assays correlates with the relative abundance of the AKR and CBR enzymes in the drug-tolerant and drug-sensitive cell lines.

Effect of DEX on In Vitro Metabolism of Anthracyclines. DEX is a potent intracellular chelating agent, and as such, it is thought to reduce the number of metal ions complexed with anthracyclines such as DOX, and consequently decrease the formation of superoxide radicals (Jones, 2008). Therefore, it is sometimes used with DOX treatment. However, the European Medicines Agency and the US Food and Drug Administration stated in June and July 2011, respectively, that the use of DEX should be restricted to adult patients who have received 300 mg/m² DOX, and general approval for use for cardioprotection was withdrawn. Nonetheless, because DEX is sometimes still used with DOX in breast cancer treatment, we decided to determine whether DEX significantly altered the metabolic conversion of DOX to DOXol. These assays were performed using intracellular fluid fractions of three of the DOX-tolerant cell lines (HepG2, HCT-15, and NCI-H460) and three of the DOX-sensitive cell lines (H9c2, PANC-1, and MCF-7). The results showed no significant effect of DEX on DOX metabolism (data not shown). Hence, if DEX does have a cardioprotective effect, it doesn’t seem to occur by impacting the primary conversion of DOX to DOXol.

Induction of AKR and CBR Enzymes in Cell Lines Following Exposure to DOX or DAUN. Next, we asked whether exposure to either DAUN or DOX induced an increase in the abundance of the AKR or CBR enzymes in one or more of the nine cell lines. In addition, if exposure to DAUN or DOX did elicit a response, then we wanted to determine whether the drug-tolerant and drug-sensitive cell types differed in their response. The cells were exposed to DOX or DAUN for 0-, 6-, 24-, and 48-hour time periods; they were then removed from the drug-containing media and, following several washes in PBS, the cells were lysed and their ability to metabolize DOX or DAUN was compared.
Fig. 2. Relative abundance of eight AKR and two CBR enzymes in the intracellular fluid of the five drug-sensitive [H9c2 (heart), PC-3 (prostate), OVCAR-4 (ovary), PANC-1 (pancreas), and MCF-7 (breast)] and the four drug-tolerant [HepG2 (liver), HCT-15 (colon), NCI-H460 (lung), and A-498 (kidney)] cell types. Densitometry was used to determine the abundance of each reductase in each cell line following Western blotting. The densitometry value for each reductase protein was normalized to the level of β-tubulin within that cell type to determine the relative abundance of each reductase in each cell type. Three independent batches of cells for each cell line were grown and subjected to Western blotting and densitometry analyses. Relative expression values are reported as mean ± S.D. (n = 3). Cell lines to the left of the vertical dotted line are sensitive to DAUN and DOX and cell lines to the right are the tolerant ones.
Finally, to determine whether any alteration in the metabolism of the drugs was correlated with induction, we measured the relative abundance of each enzyme in the cell lines following exposure to the drug for each of the time periods.

As seen in Fig. 3, after a 6-hour exposure to the drug, all nine cell lines exposed to DOX and eight of the nine cell lines exposed to DAUN (the exception was the lung cell line) had an observable increase in the activity of the AKR and CBR enzymes; however, while the increase in metabolic activity was consistently observed and easily quantified, it was not statistically significant. Statistically significant increases in DAUN/DOX metabolism were observed after 24 hours, and even greater increases were observed among the cells exposed for 48 hours. Indeed, all nine cell types responded similarly; they all upregulated their ability to metabolize DAUN or DOX. There was a 1.4- to 2.2-fold increase in DAUNol and 1.8- to 2.0-fold increase in DOXol production in all nine cell types after 24 and 48 hours of exposure to DAUN and DOX, respectively. There was no difference in the relative magnitude of induction of the AKR and CBR enzymes in response to DAUN or DOX exposure between the cells comprising the drug-tolerant group and those comprising the drug-sensitive group. However, since the drug-tolerant group had a significantly higher initial ability to metabolize the anthracyclines, and the level of induction of anthracycline-metabolizing enzymes is approximately the same in all cell lines, the drug-tolerant cell lines maintain their higher capacity for the metabolism of DOX and DAUN after exposure to these drugs.

Undoubtedly, the induction of enzyme activity required some time, since after a 6-hour exposure to either drug the increase in metabolic activity was unequivocally evident but not statistically significant. This time interval accords with the time required for transcription, translation, and accrual of the AKR and CBR enzymes. Hence, it is reasonable to speculate that the increase in metabolic activity in response to exposure to DAUN or DOX is at least partially caused by the increase in the amount of the various AKR and/or CBR enzymes. To test this hypothesis, Western blot analyses were used to examine the relative abundance of two enzymes (AKR1C3 and CBR1) in each of the nine cell lines exposed to DAUN or DOX for 0, 6, 24, or 48 hours. These two enzymes were chosen because our previous in vitro studies demonstrated that AKR1C3 and CBR1 have the highest catalytic efficiency ($k_{cat}/K_m$) toward DOX and DAUN, respectively, compared with the eight remaining AKR and CBR enzymes (Bains et al., 2010b). The Western blot analyses (Fig. 4) demonstrated that the relative abundance of AKR1C3 and CBR1 increased over time in all nine cell lines exposed to either DAUN or DOX. An easily quantified, but statistically nonsignificant, increase in these enzyme levels was observed after 6 hours. After 24 hours of exposure, all cell lines showed statistically significant increases in the abundance of AKR1C3 and CBR1. For AKR1C3, significant increases in expression were detected in both the 24- and 48-hour DAUN-treated (1.2- to 2.3-fold increase compared with nontreated cell lines) and DOX-treated (1.2- to 2.7-fold increase) cell lines. There was a comparable increase in CBR1 expression among cells exposed for 24 and 48 hours to either DAUN (1.3- to 2.8-fold increase) or DOX (1.5- to 2.4-fold increase). With each of the cell lines, whether pretreated for 6, 24, or 48 hours, plotting the increase in both DAUN/DOX metabolic activities against the abundance of AKR1C3/CBR1 revealed a strong association between these variables [coefficients of determination ($r^2$) were $>0.80$]. Thus, the induction in AKRs and CBRs appears to be the major source for the increase in DAUN and DOX metabolism observed among cell lines exposed to these drugs versus their untreated counterparts. Previous studies have demonstrated significant induction of AKRs and CBRs in the presence of DOX. For example, exposure of MCF-7 breast tumor cells to low (nanomolar) concentrations of DOX resulted in a significant increase in CBR1 protein levels (Gavelová et al., 2008), as well as AKR1C2 and AKR1C3 (Veitch et al., 2009). In relation to DAUN, the current study was the first to demonstrate that exposure to this anthracycline causes a significant induction in the expression of the CBR1 and AKR1C3 enzymes, and to show that this induction occurs in a wide variety of cell types.
Association between Cytotoxicity and DOX/DAUN Metabolism in Cell Lines Exposed to These Anthracyclines. For each of the incubation time periods, the LC50 values (DAUN and DOX) from the cytotoxicity studies were logged and plotted against the metabolic activity rates from the DAUN- and DOX-treated cell lines to see if an association exists between these two variables (Fig. 5). The high values obtained for correlation coefficients (r) and coefficients of
determination ($r^2$) suggest that anthracycline-induced cytotoxicity and metabolism show a strong, inverse correlation.

**Discussion**

DAUN and DOX are commonly used to treat a variety of cancers, but there is considerable interpatient variability in both the efficacy and toxicity of these drugs. One hypothesis is that this variability arises from the amount of drug metabolized and consequently eliminated from the body. There is no conclusive evidence linking altered DAUN or DOX metabolism to toxicity, and the argument is further encumbered by conflicting assertions of whether cytotoxicity is caused by the parent drug or its major metabolite. To address these issues, we performed in vitro studies on nine different cell lines to determine 1) whether the parent drugs, DAUN or DOX, or their major metabolites, DAUNol or DOXol, respectively, are more cytotoxic; 2) the efficiency with which each cell line metabolizes the parent drug to its major metabolite; and 3) whether the metabolic capability of each cell line correlates with the relative abundance (expression) of AKR and CBR enzymes.

The findings from the cytotoxicity studies with the parent drugs led to the allocation of nine cell lines into two distinct subgroups, drug-sensitive and drug-tolerant. The drug-sensitive group comprises five cell lines (heart, prostate, ovary, pancreas, and kidney), which comprise the drug-tolerant group (Table 1 and 2). LC50 values also indicated that the major metabolites are significantly less cytotoxic than their respective parent drugs.

One could argue that these differences in cytotoxicity are due to the accumulation or efflux of the parent drugs or major metabolites. Permeability assays were performed to measure intracellular DOX and DOXol levels of three drug-tolerant and drug-sensitive cell lines following their exposure to either compound for varying lengths of time. DAUN and DAUNol were not used because these compounds would likely yield similar findings because of similarities in chemical structure to DOX and DOXol. The intracellular concentration of DOX was significantly higher than that of DOXol among all six cell lines that were exposed to DOX versus DOXol, despite duration of exposure (compare Tables 3 and 4). All six cell lines tend to accumulate DOX with similar efficiency, as demonstrated with the intracellular levels following 20 minutes of exposure to the parent drug (Table 3). As exposure time increased to 24 hours, intracellular DOX levels among the drug-sensitive cell types were significantly higher compared with the drug-tolerant cell types. Moreover, higher intracellular DOXol levels were seen among all six cell lines as exposure duration increased regardless of whether DOXol was generated by metabolism (cells exposed to the parent drug) (Table 5) or by influx of DOXol (cells exposed to the metabolite) (Table 4). Although intracellular levels of DOXol were measured, extracellular levels were found to be least three times higher (compare Tables 5 and 6), suggesting that efflux of this metabolite occurs readily and does not limit its accumulation in the cytosol or nuclear fluid. In addition, intracellular and extracellular DOXol levels were significantly higher with the drug-tolerant cell lines versus the drug-sensitive cell lines after 6 and 24 hours of parent drug exposure. Overall, the cytotoxicity and permeability data provide considerable evidence that the parent drug is likely more cytotoxic than the major metabolite.

Because previous studies revealed DOXol or DAUNol as the major metabolites in cancer patients receiving treatment with DOX or DAUN, respectively (Lipp and Bokemeyer, 1999; Plebuch et al., 2007), we assessed the efficiency with which all nine cell lines metabolize DOX and DAUN by quantifying the rate at which the major metabolites were produced. Clearly, all nine cell types were able to metabolize either DAUN or DOX, but they differed in the rate at which they converted the parent drug to its major metabolite. The four drug-tolerant cell types metabolized DAUN or DOX faster than the five drug-sensitive cell types. The classification of cells into drug-tolerant versus drug-sensitive groups based on cytotoxicity studies correlates very well with their metabolic efficiency (correlation coefficients range from about 0.92 to 0.97, depending on exposure times, with correspondingly robust coefficients.

![Fig. 5. Scatterplot of cytotoxicity (log$_{10}$ LC50 values) and metabolic activity following DAUN (A) and DOX (B) treatment in the nine cell lines for the purposes of seeing if there is an association between these two variables. Low log$_{10}$ LC50 values are synonymous with higher cytotoxicity, while the reverse is true for high log$_{10}$ LC50 values. The high correlation coefficient (r) and coefficient of determination ($r^2$) values provided for each of the exposure time periods suggest a strong correlation between cytotoxicity and metabolism.](image-url)
of determination). Thus, there is a very strong association between these two physiologic phenomena.

Finally, the relative abundance of AKR and CBR enzymes in the nine different cell lines correlated with the relative efficiency with which each cell type metabolized DAUN or DOX. The cell lines that metabolized the drugs rapidly had considerably more intracellular AKR and CBR enzyme (often 2- to 3-fold greater) than the amount present in the cell types that metabolized the drugs slowly. Therefore, there is a striking parallel between the efficiency with which each cell type metabolizes DAUN or DOX and the relative abundance of the anthracycline-metabolizing enzymes. The drug-tolerant cell lines metabolized DAUN or DOX more quickly and they exhibited higher abundance of AKR and CBR enzymes, while the reverse was true for the drug-sensitive cell lines. When these data are taken together with the permeability data, it suggests that the difference between the drug-tolerant and drug-sensitive cell types is the rate at which they metabolize the parent drugs, DAUN and DOX. When paired with the cytotoxicity data, they provide compelling evidence that DAUN and DOX are more cytotoxic than their major metabolites.

Some caveats should be stated. First, the cells used are permanent cell lines derived from human or rat tissues. As immortalized cells, their growth properties have been altered; yet we reckon that these cell lines retain most of the biochemical distinctiveness of their respective parent cell types. Second, although there is a striking inverse relationship between the relative abundance of the selected AKR/CR enzymes and the sensitivity of each cell line to DAUN/DOX-induced cytotoxicity, the findings do not establish a direct involvement of any of these reductase enzymes with drug sensitivity. Nonetheless, we believe the results provide a compelling reason for additional studies to determine the basis for the correlation between AKR and CBR abundance and cytotoxicity following exposure to these anthracycline drugs. Future studies should include 1) inhibiting or reducing the metabolic activity of AKRs and CBRs (via knockdown/knockout procedures or the use of specific inhibitors) in cell lines with high levels of reductase expression and DAUN/DOX metabolic activity to determine whether this increases the cell’s sensitivity to the anthracycline drugs; and 2) overexpressing the individual AKRs and CBRs (via transfection with expression vectors containing the reductase gene of interest) in cell lines with low levels of reductase expression/metallic activity to see if this decreases the cell’s sensitivity to the drugs. A couple of studies of this sort have been performed. For example, Tak et al. (2011) demonstrated that overexpression of human CBR1 in hepatocellular carcinoma cells enhanced cell survival by decreasing oxidative stress under DOX treatment. Another study found that inhibiting AKR1C with 5β-cholanic acid in ABCB1-deficient cells that had become DOX-resistant restored their sensitivity to DOX while having no effect on an ABCB1-expressing epirubicin-resistant cell line (Veitch et al., 2009). For the remaining AKRs and CBRs, there are currently no published studies that examine the effects that altering their expression levels may have on cell viability in the presence of either DAUN or DOX.

Overall, our study demonstrates an inverse association between DAUN/DOX metabolism by AKRs/CBRs and cytotoxicity using nine cell lines. If this cytotoxicity is mechanistically similar to the toxicity observed following anthracycline therapy in cancer patients, then one would expect that the relative toxicities among the nine cell lines would parallel the relative sensitivity of normal cells in the tissue types from which the cell lines were derived. The heart cell line was the most sensitive to either DAUN or DOX, while the liver cell line was the most tolerant. This difference correlates with the abundance of the AKR and CBR enzymes, which is lower in heart tissue than liver (Bains et al., 2010b). This is not unexpected because these anthracyline drugs are processed primarily in the liver. A study by O’Connor et al. (1999), using Western blot analyses, demonstrated that AKR7A2 and AKR1B1 are also expressed in the human heart; unfortunately, they did not quantify the relative abundances of these two enzymes.

Given the correlation between the efficiency with which each cell line metabolizes DAUN or DOX and their sensitivity to the cytotoxic effects of these drugs, one might predict that cancer patients with mutant alleles of AKR and CBR genes that reduce enzyme function are more likely to develop toxicities following DAUN or DOX therapy. Clinical studies that compare patients with natural variants in one or more of these AKR and CBR genes to those with normal alleles are needed to determine if one or more of these variants are clinically relevant genetic biomarkers for guiding anthracycline therapy. Very recently, a variant of CBR3 was shown to be associated with changes in short-term functional cardiac parameters in patients who have undergone anthracycline therapy (Volkan-Salanci et al., 2012). However, no association was found between DAUN therapy and cardiotoxicity in a small study of 13 naturally occurring nonsynonymous single nucleotide polymorphisms in the AKRs and CBRs of 185 cancer patients (Lubieniecka et al., 2012).

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Authorship Contributions
Participated in research design: Bains, Szeitz, Lubieniecka, Cragg, Grigliatti, Reid, Riggs.
Conducted experiments: Bains, Cragg, Szeitz.
Contributed new reagents and analytic tools: Szeitz.
Performed data analysis: Bains, Cragg, Szeitz, Grigliatti.
Wrote or contributed to the writing of the manuscript: Bains, Szeitz, Lubieniecka, Grigliatti, Reid, Riggs.
Other: Riggs, Reid, and Grigliatti acquired funding for the research.

References
Anthracycline Toxicity Linked to Metabolism by Reductases


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