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Chapter

Coexisting molecular determinants of acquired oxaliplatin resistance in human colorectal and ovarian cancer cell lines

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Submitted

Abstract

Oxaliplatin is effective in combination chemotherapy of colon cancer. However, its efficacy is frequently limited by drug resistance phenomena. To gain insight into modalities of drug resistance, oxaliplatin (OHP) resistance was established in colorectal cancer cell lines LoVo-92 and LoVo-Li and a platinum-sensitive ovarian cancer cell line, A2780. Characterization of OHP-resistant cell lines included cellular platinum accumulation, formation of platinum-DNA adducts, quantitative expression of relevant transporters and DNA repair genes, gene expression arrays and array-CGH profiling. Pulse (4hr, /4OHP) and continuous exposure (72hr, /cOHP) resulted in 4.0-7.9-fold and 5.0-11.8-fold drug resistance, respectively. Cross-resistance to cisplatin was observed in OHP-resistant ovarian but not in colon cancer cells. LoVo-92 variants and A2780/cOHP showed both decreased cellular oxaliplatin accumulation and DNA-adduct formation. Sensitivity to OHP was correlated to cellular platinum accumulation, which was significantly correlated with OCT1-3 expression. ATP7A was correlated with DNA adduct formation. Gene expression profiling and pathway analysis showed significantly altered p53 signaling, Xenobiotic metabolism, Role of BRCA1 in DNA damage response and Aryl Hydrocarbon Receptor signaling pathways. Decreased expression of ALDH1L2, Bax and BBC3 (PUMA) and increased expression of aldo-keto reductases C1 and C3 were observed in these pathways. Moreover, array-CGH profiles showed mainly focal aberrations which were most prominent in drug resistant ovarian cancer cell lines. In conclusion, OHP resistance was highly correlated with total platinum accumulation as result of OCT1-3 expression status. Furthermore, apoptosis resistance via decreased expression of pro-apoptotic genes and increased expression of inhibitors of apoptosis genes (IAPs) and increased homologous repair also appeared to contribute to OHP resistance.

Introduction

Oxaliplatin is a third generation analogue of cisplatin and has shown remarkable clinical activity in colon cancer with intrinsic resistance to cisplatin. Oxaliplatin is mostly active in combination with other drugs including 5-fluorouracil with leucovorin and irinotecan (CPT11), for which response rates of up to ~60% were reported (1). Formation of platinum-DNA adducts is believed to mediate the pharmacological activity of oxaliplatin, thereby resulting in growth arrest and subsequent apoptosis (2). Similar to cisplatin, oxaliplatin-resistance can be achieved via several modalities including reduced drug uptake and/or enhanced efflux of the drug, intracellular sequestration, decreased DNA adduct formation, increased DNA repair, or increased adduct tolerance and reduced response to the platinum DNA adducts (3, 4). Cellular

accumulation of oxaliplatin is a net result of uptake and efflux. Oxaliplatin uptake can be mediated by the human copper transporter hCTR1, as well as by the organic cation transporters OCT1, 2 and 3 (SLC22A1-3) (5-8). For the efflux or sequestration of oxaliplatin, P-type ATPases including ATP7A and ATP7B appear to play a functional role (6, 9, 10). As a consequence of decreased oxaliplatin transport, the formation of platinum-DNA adducts may be diminished. Detection of platinum DNA adducts and downstream signaling is possibly the most important difference between cisplatin and oxaliplatin which might be responsible for oxaliplatin activity in colon cancers that are intrinsically resistant to cisplatin (11). For full pharmacological activity, cisplatin relies on the mismatch repair (MMR) system. In contrast, oxaliplatin is also active in MMR-deficient cells (11-14). The nucleotide excision repair system (NER) involved in repair of oxaliplatin-DNA adducts has predictive value for the treatment of colorectal cancer (15, 16). Established downstream factors that influenced sensitivity or resistance to oxaliplatin include defects in pro-apoptotic genes Bax or delayed activation of both Bax and Bad and subsequent reduction of mitochondrial transmembrane potential (17, 18). The importance of the mitochondria for oxaliplatin activity was further demonstrated in anucleated cells in which oxaliplatin retained its ability to induce apoptotic response indicating that there are multiple mechanisms of action(18). In the apoptotic response, p53 plays an important role and it has been demonstrated that inactivation or mutated p53 alters the cytotoxicity of cisplatin (19-21). Although targeted inactivation of p53 in HCT116 cells decreased the activity of oxaliplatin, it was not possible to predict sensitivity based on p53 status in a group of 30 colorectal cancer cell lines(22).

Clearly, subtle differences in determinants of cisplatin and oxaliplatin resistance exist which may be tissue-specific and possibly influenced by p53 expression. To further dissect out mechanisms of oxaliplatin resistance we here induced resistance in colon cancer cells with different p53 functional status and compared this to ovarian cancer cells. Resistance towards oxaliplatin was studied in relation to common mechanisms of drug resistance including cellular drug accumulation, expression status of relevant uptake and efflux transporters, and formation, retention and repair of platinum DNA-adducts. Since the underlying pathways that mediate resistance towards oxaliplatin are poorly described, we also investigated alterations in gene expression in the drug resistant cell lines and explored whether or not these changes are a result of aberrations at the genomic level.

Materials and methods

Chemicals Oxaliplatin (I-OHP) was kindly provided by Sanofi-Synthelabo (Paris, France). Cisplatin (CDDP, Platinol®) was obtained from Bristol-Myers Squib B.V. (Woerden, The Netherlands) in a concentration of 0.5 mg/ml. RPMI and DMEM culture medium were obtained from BioWhittaker (Cambrex BioScience, Verviers, Belgium) and fetal calf serum (FCS) was from GIBCO (Paisley, UK). All other chemicals were of analytical grade. Solutions were made in water purified by a Millipore Reagent Q system (Millipore, Bedford, USA).

Cell culture.

The colon carcinoma cell lines LoVo-92 and LoVo-Li were kindly provided by Dr. Poupon (23). LoVo-92 expresses wild-type (wt) p53 and its derivative Lovo-Li has functionally inactive p53. The functional activity of LoVo-Li was determined by co-transformation of LoVo-Li cDNA with an ADE2 open reading frame under the control of a p53-responsive element into yeast. Yeast transformed with LoVo-Li cDNA resulted in 40% red colonies that did not express ADE2 while LoVo-92 resulted in 15% red colonies (23). The p53 status was confirmed in our laboratory and was stable after trypsinization and further culturing (24). The ovarian cancer cell line A2780 expresses wt-p53. All cell lines were cultured in RPMI-1640 supplemented with 10% heat-inactivated FCS at 37°C in a humidified atmosphere of 5% CO₂ and tested within the last 6 months by morphology check by microscope and growth curve analysis according to the Cell Line Verification Test Recommendations (ATCC-Technical Bulletin No. 8, 2008). Periodic assays were performed to check for mycoplasma contamination.

Establishment of oxaliplatin resistance

Resistance to oxaliplatin was induced by exposing LoVo-92, LoVo-Li and A2780 cells to increasing concentrations of oxaliplatin using two different schedules for a period of 7 months. In the first schedule, cells were exposed to 4 hr pulses every passage to mimic the clinical bolus treatment. In parallel, cells were exposed every passage for 72 hr to mimic a continuous infusion. Platinum-resistant cell lines were termed after the parental cell line with /4OHP and /cOHP extensions reflecting the resistance induction scheme. To maintain the resistance phenotype, cells were regularly exposed to oxaliplatin during routine culturing.

Growth inhibition experiments

Growth inhibition experiments were performed at least three times using the SRB assay as previously described (25). Briefly, cells were plated in triplicates in

their specific culture medium (0.1ml/well) in flat bottom 96-well plates (Costar, Cambridge, MA, USA) in densities related to their growth (26). After 24 hr, culture medium was added to control wells (0.1ml/well) whereas drug containing culture medium was added to the other wells and subsequently cultured for another 72 hr. The drug concentration range used for CDDP was from 0.1 to 500 μM whereas that for oxaliplatin was 0.01 to 200 μM . To determine growth inhibition, cells were fixed with trichloroacetic acid (TCA) and stained with sulorhodamine B (SRB) protein dye. Optical density was measured at 540 nm and results were expressed relative to the control growth. 50% growth inhibition concentration (IC₅₀) was determined from the growth curves.

Oxaliplatin accumulation and formation of DNA adducts To determine cellular oxaliplatin accumulation and formation of DNA adducts, cells were exposed to 200 μM I-OHP for 24 hr and to determine retention of the accumulated I-OHP and the formed DNA adducts, indicative for alterations in efflux or repair, cells were subsequently incubated for 3 hr in drug-free medium as described previously (27). Cells were subsequently washed 3 times with ice-cold PBS and attached cells were harvested on ice by trypsinization, counted (for accumulation studies) and stored as cell pellets at -20°C until analysis. For determination of accumulated I-OHP, cells were lysed in 0.5 ml 2 M NaOH and incubated overnight at 55°C . Subsequently, 1 ml 1 M HCl was added and samples were measured using flameless atomic absorption spectrometry (FAAS, Varian SpectrAA-300 Zeeman Atomic Absorption Spectrometer) as described previously for CDDP (28) including a calibration curve ranging from 0.2 μM to 3.0 μM . To determine formation of platinum-DNA adducts, DNA was isolated using a QIAmp DNA Mini Kit (Westburg, Leusden, The Netherlands) and concentration was determined by measuring optical density at 260 and 280 nm (Nanodrop ND-1000, Isogen Life sciences BV, IJsselstein, The Netherlands). To DNA samples or Pt-standard solutions (ranging from 0.25 μM to 1.5 μM), 25 μl of 1.68 M NaCl was added to 250 μl and samples were subsequently measured using FAAS as described above.

Quantitative gene expression measurement

To determine gene expression, RNA was isolated from cell pellets using Trizol (Invitrogen, Paisley, UK) according the manufacturer's protocol. After RNA quantification (Nanodrop ND-1000), 500 to 1500 ng of RNA were used for cDNA synthesis as described previously (29). Subsequently gene expression was quantified using Taqman. To establish a calibration curve, human reference RNA (Stratagene, Amsterdam, The Netherlands) was used. Taqman gene expression assays were: Hs00427554_m1 (SLC22A1, OCT1), Hs00533907_m1 (SLC22A2, OCT2), Hs00222691_m1 (SLC22A3, OCT3), Hs00156229_m1 (hCTR1), Hs00163707_m1

(ATP7A), Hs00163739_m1 (ATP7B), Hs00157415_m1 (ERCC1) and Hs99999903_m1 the endogenous control human ACTB (β -actin) (27).

Microarray analysis of RNA and DNA

Parental cell lines and their oxaliplatin-resistant sublines were subjected to microarray analysis. Both array Comparative Genomic Hybridization (aCGH) and mRNA expression arrays were performed. Isolation of genomic DNA (gDNA) for aCGH analysis was performed using the Wizard Genomic DNA Purification kit (Promega Benelux, Leiden, The Netherlands) according to the manufacturer's protocol. Total RNA was isolated using Trizol extraction as described above. The gDNA and RNA quality was checked ($OD_{260/280} > 1.8$). Subsequently, aCGH was performed using the Agilent Human Genome CGH 44K array platform (Agilent Technologies, Amstelveen, The Netherlands). Samples and human universal reference were hybridized using a cross array hybridization as described previously(30). For mRNA expression, the Agilent Whole Genome Oligo Microarray 4x44K array platform was used according to the manufacturer's protocol. Samples of drug-resistant cell lines were hybridized to their parental cell lines.

Microarray data analysis

After hybridization and scanning of aCGH slides the raw data were extracted from the images using Agilent Feature Extraction (version 9.5.1.1). Subsequently, data were normalized and smoothed with the R-script "Nowave" to increase accurate detection of breakpoints(31). Genomic aberrations and breakpoints were determined using CGHcall which determines the probability of detected gains and losses (32). For detection of copy number induced differential gene expression, CGHcall data and mRNA expression data were subsequently analysed using Ace-it (33).

After hybridization and scanning of slides for genome wide gene expression, the raw data were extracted from the images using Agilent Feature Extraction and subsequently processed using the LIMMA package in Bioconductor to determine Lowess-normalized Log₂ ratios. For determination of enrichment of genes in canonical pathways, normalized Log₂ ratios >1 or <-1 and $p < 0.05$ were analysed using Ingenuity Pathway Analysis (Ingenuity Systems, Redwood City, USA).

Results

Growth inhibition

The results of the growth inhibition experiments aimed at determining the degree of drug resistance induced by exposure to gradually increasing concentrations of

Table 1. Sensitivity to oxaliplatin and cisplatin in parental and drug resistant variants of colon and ovarian cancer cell lines

| Cell line | I-OHP (μM) | CDDP (μM) | RF (I-OHP) | RF (CDDP) |
|--------------|-------------------------|------------------------|------------|-----------|
| LoVo-92 | 0.21 \pm 0.04 | 1.50 \pm 0.40 | | |
| LoVo-92/4OHP | 1.69 \pm 0.25 | 2.50 \pm 1.31 | 7.9 | 1.7 |
| LoVo-92/cOHP | 2.51 \pm 0.25 | 4.03 \pm 1.64 | 11.8 | 2.7 |
| LoVo-Li | 0.75 \pm 0.08 | 4.23 \pm 1.65 | | |
| LoVo-Li/4OHP | 3.03 \pm 0.64 | 4.65 \pm 0.35 | 4.0 | 1.1 |
| LoVo-Li/cOHP | 4.23 \pm 0.92 | 7.57 \pm 1.23 | 5.6 | 1.8 |
| A2780 | 0.32 \pm 0.03 | 0.50 \pm 0.14 | | |
| A2780/4OHP | 1.73 \pm 0.40 | 3.50 \pm 2.25 | 5.3 | 7.0 |
| A2780/cOHP | 3.61 \pm 0.33 | 4.60 \pm 0.70 | 11.1 | 9.3 |

Colon (LoVo) and ovarian (A2780) cancer cell lines were made resistant by weekly 4 hr (/4OHP) and 72 hr (/cOHP) exposure to increasing concentration of oxaliplatin. IC₅₀ values and resistance factors (RF) were determined after 72 hours exposure to I-OHP and CDDP. Values are given in μM and are Means \pm SEM of at least 3 separate experiments.

oxaliplatin over 7 months and cross-resistance to cisplatin are shown in Table 1. The colon cancer cell line LoVo-92 was most sensitive to oxaliplatin with an IC₅₀ value of 0.21 μM . Induction of resistance after 4 hr oxaliplatin pulses resulted in 7.9 fold resistance and after continuous drug exposure in 11.8 fold resistance. LoVo-Li cells that express inactive p53 were 3.5 fold less sensitive to oxaliplatin and the resistant variants showed a similar pattern of resistance towards oxaliplatin as the wt p53 parental cell line LoVo-92 with resistance factors of 4.0 and 5.6 for LoVo-Li/4OHP and LoVo-Li/cOHP, respectively. Remarkably, these LoVo-92 and LoVo-Li variants retained parental cell sensitivity to cisplatin. Moreover, the oxaliplatin-resistant sublines of the ovarian cancer cell line A2780 displayed higher resistance levels after continuous exposure to oxaliplatin than after 4 hr pulses, hence being 11.1- and 5.3 fold, respectively. In contrast to the colon cancer cell lines, these oxaliplatin-resistant ovarian cancer cells were also cross-resistant to cisplatin; 7.0- and 9.3 fold for A2780/4OHP for A2780/cOHP, respectively.

Cellular oxaliplatin accumulation and formation of DNA adducts

In order to determine whether or not oxaliplatin resistance is mediated by reduced drug uptake or increased efflux which might result in decreased formation of platinum DNA adducts, cellular drug accumulation and DNA adduct formation were determined (Figure 1A). LoVo-92/4OHP and LoVo-92/cOHP showed a marked reduction (~60%) in cellular accumulation of platinum.

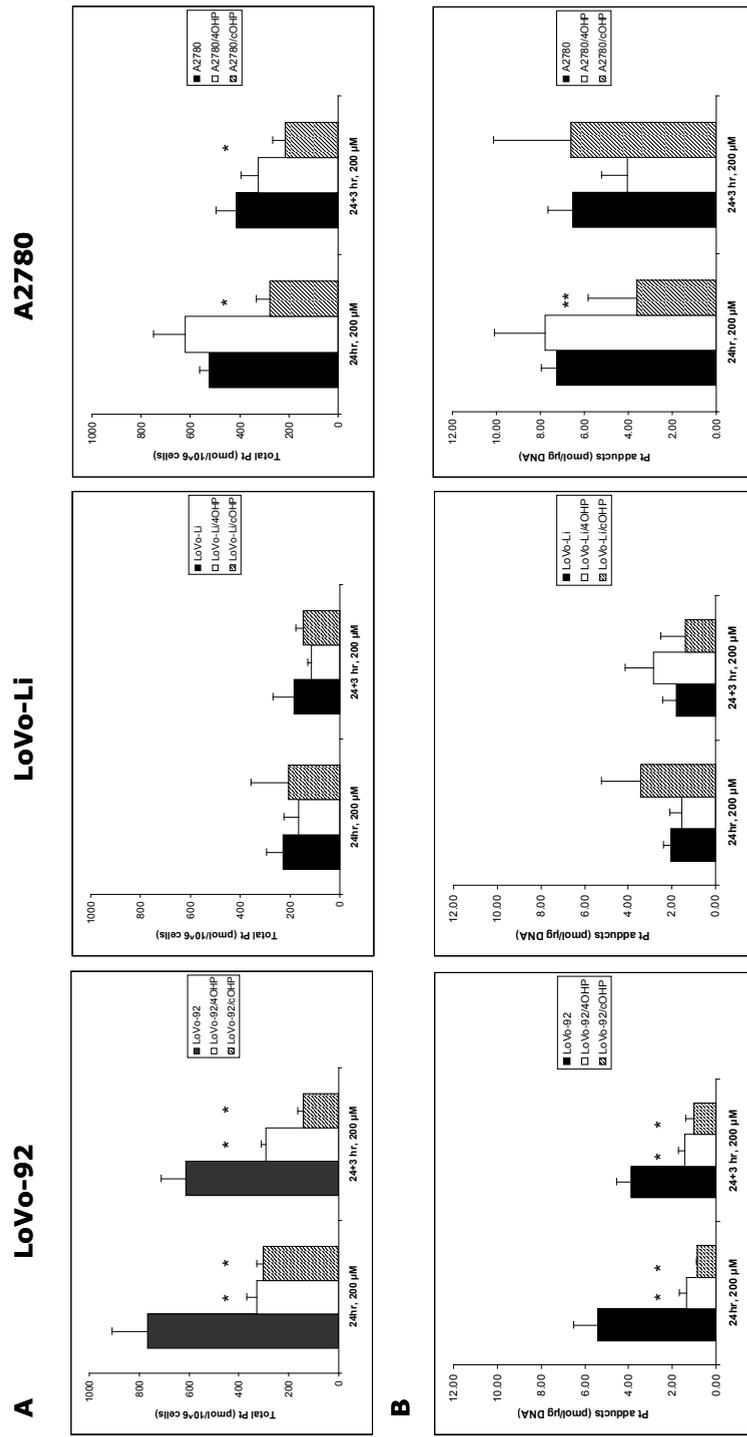


Figure 1. Total platinum accumulation (A) and platinum DNA adducts formation (B) in LoVo-92 variants, LoVo-Li variants and A2780 variants. Values are means \pm SEM of at least 3 experiments and expressed as pmol/10⁶ cells (A) and as pmol/mg DNA (B). Cells were exposed for 24 hours to 200 μ M Oxaliplatin and, in parallel, for 24 hours followed by 3 hours in drug-free medium. Significant changes ($p < 0.05$) compared to parental cell lines are marked with * while ** was close to significance ($p = 0.055$).

We also explored the possibility of increased platinum efflux; hence, after removal of the drug and incubation for 3 hr in drug-free medium, LoVo-9274OHP showed a 10% reduction in the accumulated oxaliplatin, similar to parental LoVo-92 cells, whereas in LoVo-92/cOHP a reduction of 50% was observed suggesting that increased efflux of oxaliplatin might contribute to resistance to oxaliplatin. LoVo-Li cells, which were less sensitive when compared to LoVo-92, showed 4-fold lower accumulation of oxaliplatin. However, no significant change in cellular accumulation of oxaliplatin was observed in the oxaliplatin-resistant variants. Removal of the drug and incubation for 3 hours in drug-free medium showed 30% reduction in both LoVo-Li/4OHP and LoVo-Li/cOHP compared to 20% for parental LoVo-Li cells. The ovarian cancer cell lines showed a mixed picture; there was no significant change in accumulation after 24 hr exposure in A2780/4OHP cells, whereas A2780/cOHP accumulation was about 50% when compared to the parental cell line A2780. Total platinum levels after removal of the drug showed a similar decrease for both parental A2780 and oxaliplatin resistant A2780/cOHP. A2780/4OHP cells showed a 50% decrease of total platinum levels after incubation in drug-free medium suggesting that increased oxaliplatin efflux may be a contributing factor to the drug resistance phenotype.

Consequent to decreased oxaliplatin accumulation, formation of platinum-DNA adducts was also decreased in LoVo-92/4OHP and LoVo-92/cOHP (Figure 1B). Removal of the drug and incubation in drug-free medium did not show decreased formation of DNA adducts suggesting that increased repair does not contribute to resistance in these cell lines. Consistent with the accumulation of oxaliplatin in LoVo-Li/4OHP and LoVo-Li/cOHP cells, the formation of DNA adducts was also not significantly altered both after 24 hr exposure as well as after additional incubation in drug-free medium. The formation of platinum DNA adducts in A2780/4OHP and A2780/cOHP reflected the pattern of total platinum accumulation in these cell lines. A2780/4OHP showed somewhat higher content of DNA adducts which might be expected of the somewhat higher accumulation of the drug, whereas in A2780/cOHP cells, formation of DNA adducts was reduced to an extent that was similar to that of cellular platinum accumulation.

Figure 2 depicts the correlation of cellular oxaliplatin accumulation, DNA adduct formation and oxaliplatin sensitivity. Figure 2A and Table 2 show that an increased cellular accumulation of oxaliplatin resulted in a consistently and significantly higher formation of DNA adducts. Figure 2B and 2C and Table 2 show that sensitivity towards oxaliplatin is highly and significantly correlated with cellular accumulation of the drug but not with the formation of platinum DNA adducts.

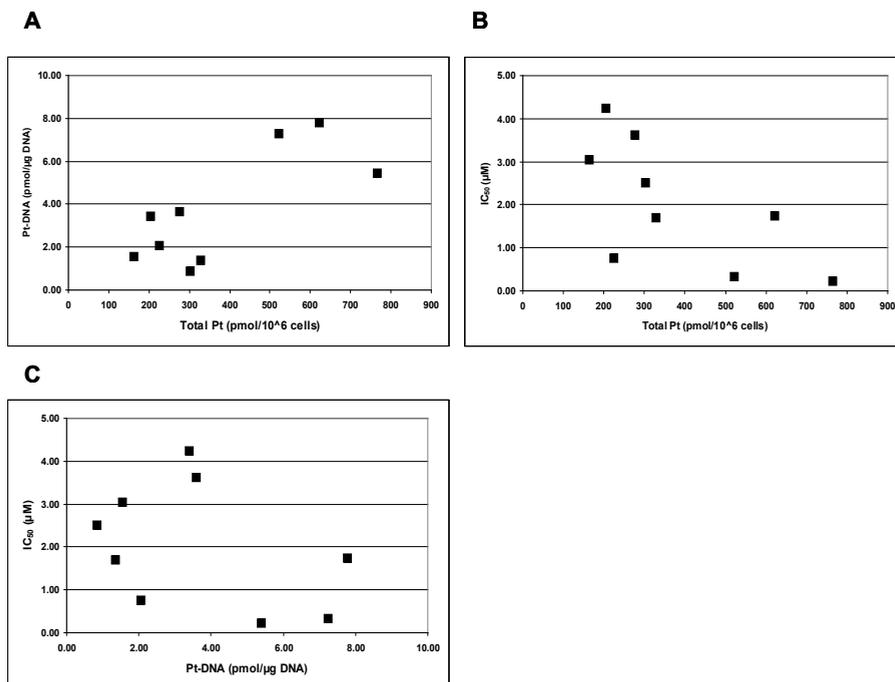


Figure 2. Relation between total platinum accumulation, platinum DNA adducts formation and sensitivity towards oxaliplatin in parental and oxaliplatin resistant cell lines. (A) Scatter plot of total platinum accumulation (pmol/10⁶ cells) and formation of platinum DNA adducts (pmol/μg DNA), (B) scatter plot of total platinum accumulation (pmol/10⁶ cells) and sensitivity (μM) towards oxaliplatin and (C) scatter plot of platinum DNA adducts formation (pmol/μg DNA) and sensitivity (μM) towards oxaliplatin (C).

Gene expression of relevant transporters and DNA repair genes

The net cellular accumulation of oxaliplatin and consequent formation of platinum DNA adducts might be affected by influx and efflux transporters as well as DNA repair. Therefore, mRNA expression of the copper transporter, hCTR1, the organic cation transporters OCT1, 2 and 3 (SLC22A1-3) as well as the efflux transporters ATP7A and ATP7B were determined by Q-PCR. The expression of nucleotide excision repair gene ERCC1 was also evaluated (Figure 3). The results for LoVo-92 and the resistant variants reflect the results of cellular oxaliplatin accumulation and DNA adduct formation experiments. Changes in gene expression levels in LoVo-92/4OHP

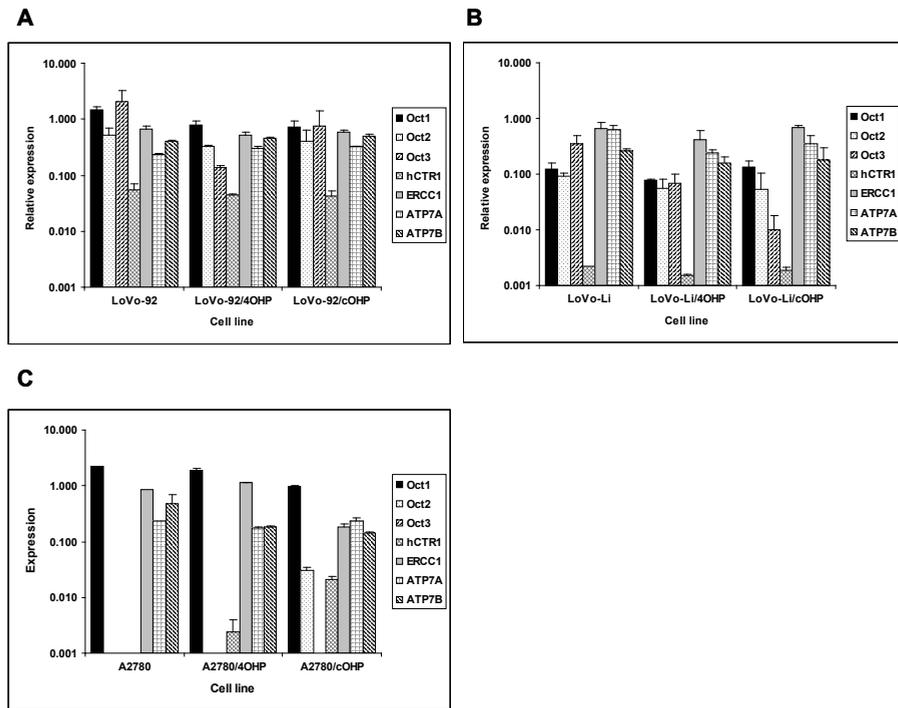


Figure 3. mRNA expression of transporters and DNA repair genes as determined by Q-PCR in (A) LoVo-92 variants, (B) LoVo-Li variants and (C) A2780 variants. Values are means of 2 experiments in triplicate and are expressed relative to the house keeping gene β -actin.

and LoVo-92/cOHP were almost similar and showed decreased expression of the influx transporters hCTR1 and OCT1, OCT2 and OCT3 with 20%, 50%, 30% and 20%, respectively. ERCC1 gene expression was decreased by 15%, whereas expression of the efflux transporters ATP7A and ATP7B was increased by 30% and 20%, respectively.

LoVo-Li cells displayed lower gene expression levels of influx transporters corresponding with lower drug accumulation and formation of oxaliplatin DNA adducts in LoVo-Li cells compared to LoVo-92. LoVo-Li/4OHP cells show decreased expression of all influx and efflux transporters, as well as the DNA repair gene ERCC1. The hCTR1, OCT1, OCT2 and ERCC1 were decreased with 40% whereas OCT3 showed decreased expression of 80%. ATP7A and ATP7B were decreased with 60% and 40%, respectively. In LoVo-Li/cOHP OCT1 and ERCC1 were unchanged, whereas the other genes showed decreased expression. Expression of the influx transporters hCTR, OCT2 and OCT3 was decreased by 15%, 40% and 95%, respectively.

Table 2. Correlation between quantitative gene expression data with total platinum accumulation, platinum-DNA adduct formation and sensitivity to oxaliplatin.

| | | Pearson correlation | | | Spearman's rho | | |
|----------|-------------|---------------------|--------|---------|----------------|---------|---------|
| | | Total Pt | Pt-DNA | IC50 | Total Pt | Pt-DNA | IC50 |
| Total Pt | Correlation | | 0.760* | -0.667* | | 0.533 | -0.700* |
| | p-value | | 0.018 | 0.050 | | 0.139 | 0.036 |
| Pt-DNA | Correlation | 0.760* | | -0.398 | 0.533 | | -0.283 |
| | p-value | 0.018 | | 0.289 | 0.139 | | 0.460 |
| OCT1 | Correlation | 0.882* | 0.841* | -0.557 | 0.867* | 0.733* | -0.467 |
| | p-value | 0.007 | 0.005 | 0.119 | 0.002 | 0.025 | 0.205 |
| OCT2 | Correlation | 0.802* | 0.152 | 0.638 | 0.714 | -0.214 | -0.821* |
| | p-value | 0.030 | 0.745 | 0.123 | 0.071 | 0.645 | 0.023 |
| OCT3 | Correlation | 0.949* | 0.688 | -0.675 | 0.771 | 0.029 | -0.829* |
| | p-value | 0.004 | 0.131 | 0.141 | 0.072 | 0.975 | 0.042 |
| CTR1 | Correlation | 0.475 | 0.145 | -0.413 | 0.762* | -0.071 | -0.619 |
| | p-value | 0.234 | 0.732 | 0.269 | 0.028 | 0.867 | 0.102 |
| ATP7A | Correlation | -0.489 | -0.494 | -0.107 | -0.644 | -0.745* | 0.259 |
| | p-value | 0.182 | 0.177 | 0.784 | 0.061 | 0.021 | 0.500 |
| ATP7B | Correlation | 0.351 | -0.054 | -0.588 | 0.517 | -0.217 | -0.617 |
| | p-value | 0.354 | 0.890 | 0.096 | 0.154 | 0.576 | 0.077 |
| ERCC1 | Correlation | 0.572 | 0.672* | -0.457 | 0.500 | 0.650 | -0.367 |
| | p-value | 0.108 | 0.048 | 0.216 | 0.170 | 0.058 | 0.332 |

Pearson and Spearman correlation analysis were performed between gene expression of transporters and DNA repair genes with total platinum accumulation, platinum DNA adducts formation and sensitivity to oxaliplatin. Depicted are the correlation coefficient and p-value. Significant correlations are marked with *.

The efflux transporters ATP7A and ATP7B showed decreased expression of 45% and 30%, respectively. The drug resistant ovarian cancer cell lines exhibited decreased expression of all transporter genes except for OCT2 and OCT3 which were not detectable in the parental cells as well in the resistant cells. Expression of OCT1 in A2780/4OHP and A2780/cOHP was decreased with 20% and 60%, respectively. ATP7A was decreased with 25% in A2780/4OHP but unchanged in A2780/cOHP. ATP7B was decreased with 35% in both A2780/4OHP and A2780/cOHP. The nucleotide excision repair gene ERCC1 showed an increased expression in A2780/4OHP but was decreased with 80% in A2780/cOHP. Pearson Correlation analysis (Table 2) of Q-PCR data with total platinum accumulation, platinum DNA adducts formation and sensitivity to oxaliplatin showed that OCT1 was significantly correlated to total platinum accumulation for all cell lines, whereas OCT2 and OCT3 were significantly

correlated with total oxaliplatin accumulation in the LoVo cell lines. Remarkably, ERCC1 was positively and significantly correlated with the formation of platinum DNA adducts. In addition, using Spearman correlation analysis, a significant correlation was found between gene expression of the copper transporter hCTR1 and total platinum accumulation, whereas ATP7A was found to be significantly correlated to formation of platinum DNA adducts. Furthermore, the expression of OCT2 and OCT3 were significantly correlated with sensitivity to oxaliplatin.

Genome-wide expression array analysis

Although in LoVo-92 variants total platinum accumulation, DNA adducts formation and transporter gene expression appear to correlate and provide adequate explanation for drug resistance, the picture for LoVo-Li and A2780 variants is less clear. We hence performed gene expression arrays to gain a better insight in the mechanisms underlying oxaliplatin resistance. Gene expression array data were significantly correlated with quantitative gene expression obtained with Q-PCR for the genes described above (data not shown). Ingenuity Pathway Analysis (IPA) of normalized log₂ ratios of the resistant cell lines and corresponding parental cell line (Gene expression omnibus: GSE19992) was used to pin-point the canonical pathways that were most significantly enriched. The most frequently and significantly enriched pathways are shown in Table 3. Gene expression levels of the most relevant pathways are shown in Supplemental Table 1.

Axonal Guidance Signaling and *Aryl Hydrocarbon Receptor Signaling* pathways were found to be significantly enriched for 4 out of 6 resistant cell lines. Expression of genes of the ALDH family was most frequently altered in the *Aryl Hydrocarbon Receptor Signaling* pathway. ALDH1L2 was decreased in all cell lines with log₂ ratios from -2.26 for A2780/4OHP to -3.45 for LoVo-Li/4OHP. The ALDH1A2 gene was increased in all cell lines except for the LoVo-Li/cOHP. Unexpectedly, resistant ovarian cancer cell lines showed decreased expression of the glutathione-S-transferase family of genes. However, microsomal glutathione-S-transferase 1 showed an increased expression in these resistant variants and to some extent also in drug-resistant colorectal cancer cell line variants.

Various signaling pathways showed major changes in the expression of their pertaining genes, which may in general point to an altered, mostly reduced capacity to induce cell death. The *p53 Signaling* pathway was significantly enriched in LoVo-Li/4OHP and in all the resistant ovarian cancer cell lines. A decreased expression of the pro-apoptotic gene Bax was the most commonly altered gene. Moreover, other pro-apoptotic genes like BBC3 (Puma) and Apaf1 also showed decreased expression. PCNA, involved in replication and DNA damage response showed increased

Table 3. Significance of most frequently observed enriched canonical pathways.

| IPA Pathway | LoVo-92 | | LoVo-Li | | A2780 | |
|--|---------|------|---------|------|-------|------|
| | 4OHP | cOHP | 4OHP | cOHP | 4OHP | cOHP |
| Axonal Guidance Signaling | 3.16 | | | 2.35 | 3.56 | 1.92 |
| Aryl Hydrocarbon Receptor Signaling | | 2.81 | | 3.95 | 2.32 | 3.06 |
| p53 Signaling | | | 1.71 | | 2.90 | 3.84 |
| Colorectal Cancer Metastasis Signaling | 2.72 | | | | 4.10 | 2.97 |
| ILK Signaling | 1.99 | | | | 3.44 | 2.57 |
| RAR Activation | 2.17 | 2.42 | | 2.11 | | 2.66 |
| Role of Macrophages, Fibroblasts and Endothelial Cells in Rheumatoid Arthritis | | 2.00 | | 2.98 | 3.93 | 2.04 |
| Virus Entry via Endocytic Pathways | | 1.78 | | 3.08 | | 3.28 |
| Agrin Interactions at Neuromuscular Junction | | 1.84 | | | | 2.71 |
| Cardiac Hypertrophy Signaling | 2.00 | | | | 2.02 | |
| Caveolar-mediated Endocytosis Signaling | | 1.71 | | | | 2.89 |
| Cysteine Metabolism | | | 1.42 | | 2.32 | 1.89 |
| Glycine, Serine and Threonine Metabolism | | | 1.48 | | 3.38 | 2.96 |
| Hepatic Fibrosis / Hepatic Stellate Cell Activation | | | | | 2.94 | 2.32 |
| Molecular Mechanisms of Cancer | | | | | 3.51 | 2.43 |
| p38 MAPK Signaling | | 1.52 | | | 3.01 | 1.95 |
| Semaphorin Signaling in Neurons | 2.45 | | | | 2.84 | |
| Sphingosine-1-phosphate Signaling | | | | | 3.11 | 2.06 |
| Starch and Sucrose Metabolism | 1.77 | | 1.40 | 4.36 | | |
| Tyrosine Metabolism | 1.83 | 1.75 | | 2.37 | | |
| Role of BCRA1 in DNA damage response | | 2.30 | 5.76 | | | |
| CXCR4 Signaling | 2.42 | | | | | |
| Metabolism of Xenobiotics by Cytochrome P450 | | | | | 9.41 | |
| Cell Cycle: G1/S Checkpoint Regulation | | | 4.63 | | | |
| Xenobiotic Metabolism Signaling | | | | 5.57 | | |

Global gene expression array data showing two fold increased or decreased expression in the resistant cell lines relative to their parental cell lines were subjected to Ingenuity Pathway Analysis (IPA). Most frequently observed enriched pathways are shown and depicted values are $-\text{Log}(p)$ determined with the Fisher Exact test.

expression both in resistant colorectal cancer cell lines as well as in ovarian cancer cell lines. Decreased expression of tumor suppressor SerpinB5 was only observed in resistant colorectal cancer variants. However, other genes involved in the *p53*

Signaling pathway showed inconsistent changes. The pro-apoptotic gene PMAIP1 (Noxa) was increased in A2780/4OHP. Cell death executors Caspase 6 and 7 were increased in gene expression in the ovarian cancer cell lines and only modest in LoVo-Li/4OHP, but in LoVo-Li/4OHP this was accompanied by an increased expression of the inhibitor of apoptosis (IAP) gene BIRC5 (Survivin) and decreased expression of BIRC4 (XIAP). The ovarian cancer cell lines showed increased BIRC4 and BIRC5 expression in A2780/4OHP and A2780/cOHP, respectively. Other genes that were strongly increased in the ovarian cancer cell lines are HIPK2 and PLAGL1. p53 was only decreased in A2780/4OHP and A2780/cOHP. The p53 induced nuclear protein 1, TP53INP1, showed decreased gene expression in all cell lines but LoVo-92/4OHP. Taken together, the pro-apoptotic pathway seemed decreased and the anti-apoptotic pathway increased, thereby possibly resulting in an overall decreased apoptotic potential in the drug-resistant cell lines.

Less frequently observed yet highly significant for the drug-resistant variants of LoVo-Li are the *Role of BCRA1 in DNA Damage Response*, *Metabolism of Xenobiotics by Cytochrome p450*, *Xenobiotic Metabolism Signaling pathways* and *G1/S checkpoint regulation*. The *Role of BRCA1 in DNA Damage Response* was most prominent in LoVo-92/cOHP and LoVo-Li/4OHP but the ovarian cancer cell lines also showed altered expression of genes in this pathway. Excluding E2F5, all genes in this pathway were increased in LoVo-Li/4OHP, whereas in LoVo-92/cOHP increased expression of BLM, CHEK1, E2F1, Rad51 and RFC2 was observed. In the ovarian cancer cell lines A2780/4OHP and A2780/cOHP the highest increase was observed for FANCA. Both *Xenobiotics Metabolism* pathways were only significantly enriched for LoVo-Li/4OHP but included genes that were found to be increased in other resistant variants as well. Most prominent was the above described ALDH family of genes. Other frequently increased genes were aldo-keto reductase family members 1C1 and 1C3 which were increased in 4 out of 6 and all drug-resistant variants, respectively. The expression of the multidrug efflux transporter ABCC2 (MRP2) was increased in oxaliplatin-resistant ovarian cancer cell lines however decreased gene expression was observed in resistant LoVo-Li variants. However, resistant LoVo-Li variants showed increased expression of another MDR efflux transporter, ABCB1 (Pgp). *G1/S Checkpoint regulation* was only significant for LoVo-Li/4OHP and showed increased expression of Cyclins D1 and D3, cyclin dependent kinases 2 and 4, E2F family members 1, 3 and 4 and also RBL1 and the transcription factor TFDP1.

Table 4. Common or overlapping chromosomal aberrations.

| Chr | Chr. band | Probe Position | Aberration | Cell lines |
|-----|---------------|-----------------------|------------|--|
| 2 | q37.1 | 232396451 - 233411853 | Focal gain | LoVo-Li/4OHP, LoVo-Li/cOHP |
| 4 | p16.3-16.1 | 6503780 - 880103 | Gain | A2780/4OHP, A2780/cOHP |
| 7 | q31.1 | 110361335 - 110795919 | Focal loss | LoVo-Li/4OHP, LoVo-Li/cOHP |
| 10 | q21.3 | 69418458 - 69551488 | Focal loss | A2780/4OHP, A2780/cOHP |
| 12 | q24.23-q24.31 | 120316650 - 120358330 | Focal gain | LoVo-Li/4OHP, LoVo-Li/cOHP |
| 15 | q22-q26.2 | 66499644 - 98087372 | Loss | LoVo-92/4OHP, LoVo-92/cOHP |
| 16 | p13.3 | 3427264 - 4180609 | Focal gain | LoVo-Li/4OHP, LoVo-Li/cOHP, A2780/4OHP |
| 17 | q21.2 | 39782285 - 39993938 | Focal gain | LoVo-Li/4OHP, LoVo-Li/cOHP, A2780/cOHP |
| 19 | p13.3 | 232080 - 637653 | Focal gain | A2780/4OHP, A2780/cOHP |
| 19 | p13.11 | 17268193 - 17536526 | Focal gain | LoVo-Li/4OHP, LoVo-Li/cOHP |

Acquired chromosomal aberrations after induction of resistance were determined with aCGH analysis. Size and location of the aberrations were determined using CGHcall. Depicted are the common or overlapping gains and losses with the chromosome (Chr) number, chromosomal band (Chr. band) and genomic position (probe position) and the cell lines in which the aberrations were observed. Focal gains and losses are defined as < 3 Mb.

Oxaliplatin induced chromosomal aberrations

To determine whether alterations in gene expression could be the result of gene copy number variations, we performed aCGH. The chromosomal profiles (normalized log₂ ratio) are shown in Supplemental Figure 1 including aberration calls of the resistant cell lines compared to parental cell lines as well as profiles of parental cell lines compared to reference DNA (Gene expression omnibus: GSE20144). Common or overlapping aberrations are summarized in Table 4.

Analysis of aCGH data for common aberrations revealed that 8 out of 10 observed common or overlapping aberrations are found in drug-resistant cell lines derived from the same parental cell line. Focal Gains observed in Chr15 and Chr16 showed that similar aberrations are also found in both resistant colon and ovarian cancer drug-resistant cell lines. Remarkably, parental LoVo-92 cells displayed a gain at Chr15 which was completely lost in LoVo-92/4OHP and partly lost in LoVo-92/cOHP cells.

Discussion

Oxaliplatin resistance is a major clinical impediment to curative chemotherapy as it is a crucial component of combination regimens for colorectal cancer. Although much knowledge has been gained regarding mechanisms underlying resistance to the first generation platinum compound cisplatin, those relating to oxaliplatin resistance are still ill characterized.

As the pharmacological activity to oxaliplatin might be affected by tissue type and treatment schedule as well as by other factors including p53 status, we established oxaliplatin resistant cell lines representing these parameters. The colorectal cancer cell lines LoVo-92 and its variant LoVo-Li as well as A2780 ovarian cancer cells were made resistant via short-term drug pulses to reflect the clinical bolus administration and compared the latter to cell lines which acquired resistance after continuous exposure to oxaliplatin. The data show moderate levels of resistance (i.e. clinically relevant) ranging from 4-12-fold when compared to parental cells. Remarkably, low level cross-resistance towards cisplatin was observed in the colorectal cell lines, whereas oxaliplatin-resistant ovarian cancer cell lines showed similar resistance levels for both cisplatin and oxaliplatin. This observation may be explained by the intrinsic cisplatin resistance of both parental colorectal cancer cell lines which are deficient in mismatch repair and an established mechanism of resistance to cisplatin but not oxaliplatin (12-14, 34). Therefore, induction of resistance to oxaliplatin may not necessarily result in cross-resistance to cisplatin. Since cisplatin-resistance levels were similar to those of oxaliplatin in the oxaliplatin resistant ovarian cancer cell lines, it is likely that similar resistance mechanisms may be operative that play a role for both platinum drugs.

Although both cisplatin and oxaliplatin are believed to exert their cytotoxic activity via formation of DNA adducts, involvement of mismatch DNA repair is different for each drug. Moreover, other pharmacological parameters such as drug transport have been reported to be different for both platinum compounds (7, 8). Accumulation of total platinum was significantly correlated with sensitivity to oxaliplatin in this panel of parental and drug-resistant cell lines in contrast to the formation of platinum DNA adducts, suggesting that alternative drug targets are important for oxaliplatin activity. Since gene expression levels of organic cation transporters was significantly correlated to total platinum accumulation, it is likely that loss of the expression of these transporters may significantly contribute to the platinum-drug resistance phenotype observed in these cell lines. Indeed, recent studies have shown that oxaliplatin is a substrate for the influx transporters OCT1-3 albeit substrate affinity for these membrane carriers varied between the different reports (7, 8, 35, 36). The relevance of OCT3 in oxaliplatin uptake in colorectal cancer was further demonstrated

by higher expression levels in tumor specimens compared to normal tissue (37). Since a high concentration of oxaliplatin was used for the accumulation experiments here, it is unlikely that the hCTR1 transporter contributed to the reduced platinum drug accumulation (5).

The lack of correlation between sensitivity to oxaliplatin and the formation of platinum DNA adducts may be the result of cellular sequestration of the drug by the ATPases ATP7A and ATP7B that play a role in intracellular trafficking and efflux of the drug (6). The efflux transporter ATP7A was significantly correlated to the formation of platinum DNA adducts and might therefore determine the formation of DNA adducts. Next to reduced accumulation and drug sequestration, platinum DNA adducts tolerance (4) might also play a role in drug resistance since no reduction in DNA adduct formation was observed in oxaliplatin-resistant LoVo-Li variants and A2780/4OHP.

To gain insight into the alternative mechanisms of oxaliplatin resistance, we also performed gene expression arrays and subjected the data to Ingenuity Pathway Analysis (IPA). Several pathways were frequently and significantly affected and might add to the resistance mechanisms described above. The most frequently altered gene in the *Aryl Hydrocarbon Receptor (AHR) signaling* pathway was ALDH1L2 and was decreased in all oxaliplatin resistant cell lines. ALDH1L2 is the mitochondrial homolog of ALDH1L1 which has been implicated in cell proliferation and apoptosis(38, 39). Another family member, ALDH1A1 was increased in 5 out of 6 drug-resistant cell lines and is a marker for cancer stem cells and chemoresistance (40). In the *p53 signaling* pathway the most frequently decreased genes were the pro-apoptotic genes BAX and BBC3 (PUMA) which were reported previously to play a role in oxaliplatin resistance(17, 18) and induction of apoptosis (41), respectively. Previously it was demonstrated that oxaliplatin decreased BIRC5 (Survivin) levels (42, 43). Increased BIRC5 expression could therefore contribute to the observed oxaliplatin resistance. Similarly, increased expression of the inhibitor of apoptosis BIRC4 (XIAP) could also contribute to oxaliplatin resistance and thereby counteract the increased expression of the cell death execution caspases 6 and 7 in the platinum-resistant ovarian cancer cell lines.

Since the expression of ERCC1 is unaltered or even decreased in the drug-resistant cell lines, it is unlikely that nucleotide excision repair is involved in the resistance towards oxaliplatin in these cell lines. Decreased ERCC1 mRNA and protein expression in oxaliplatin resistant cells has been previously demonstrated by Stordal et al (44) and was correlated to cell cycle response rather than to DNA repair after platinum treatment. The *Role of BRCA1 in DNA damage response* pathway was significantly changed particularly in the LoVo-92/cOHP and LoVo-Li/4OHP cell lines. Increased expression of RAD51, Fanconi genes A, G and M and Replication Factor 2 and 5

suggest that homologous repair of double strand breaks could contribute to oxaliplatin resistance in these cell lines.

The *Xenobiotic Metabolism* pathways suggested a possible contribution to oxaliplatin resistance of aldo-keto reductase family members 1C1 and 1C3. Aldo-keto reductase family members have been implicated previously in poor prognosis and resistance towards platinum and other drugs(45-47). Contrasting results were observed for the multidrug resistance efflux transporter ABCC2 (MRP2) which was decreased in LoVo-Li variants but increased in the A2780 variants, hence this ABC transporter does not appear to contribute to oxaliplatin efflux. Previously we compared 2008 ovarian cancer cells and a ABCC2 (MRP2) transfected variant for oxaliplatin sensitivity but observed no difference in growth inhibition (data not shown). However, recent data suggest the possible involvement glycosylation of MRP family members 1 and 4 in oxaliplatin resistant ovarian cancer cell lines which was associated with decreased platinum drug accumulation(48).

Changes in gene expression observed in the drug resistant cell lines as discussed above could be mediated by altered gene expression but might also be a result of gains and losses at the genomic level. Primarily focal gains and losses were observed in the oxaliplatin resistant variants. The parental cell line LoVo-92 has been characterized by trisomy of Chromosome (Chr) 5, 7 and 15(49). The major loss of Chr 15 in LoVo-92/4OHP suggests that the trisomy of Chr 15 was lost. In LoVo-92/cOHP only a partial loss of Chr 15 was observed. LoVo-Li which was derived from LoVo-92 also showed a gain of Chr 12p that was retained in the drug resistant variants. Comparison of the aCGH profiles with mRNA expression data using the program ACE-it (data not shown) did not reveal common genes that were significantly altered both at the genomic and mRNA level. Previously it was shown that in H69 small cell lung cancer cells oxaliplatin induced three times more chromosomal alterations than cisplatin (50). Since the resistant variants of the ovarian cancer A2780 cells harbor a much higher number of chromosomal aberrations, this suggests that these cells are more vulnerable to oxaliplatin than the colorectal cancer cell lines LoVo-92 and LoVo-Li. In H69 cells it was shown that after removal of the drug and loss of the drug resistance phenotype, many of the aberrations observed in the drug resistant variants were lost but some were retained (50). It was hence concluded that the similar changes found after treatment with cisplatin and oxaliplatin were independent of the drug resistance phenotype.

One of the main findings of the present study is that sensitivity to oxaliplatin is highly correlated with total platinum accumulation which was significantly associated with expression status of the organic cation transporters OCT1-3, hence highlighting the role of these influx transporters in acquisition of oxaliplatin resistance. Since

formation of DNA adducts, which was highly correlated to ATP7A, was not related to oxaliplatin sensitivity, it can be concluded that mechanisms other than DNA damage signaling may contribute to the pharmacological activity of oxaliplatin. Decreased expression of pro-apoptotic genes as Bax and BBC3(PUMA) and increased expression of inhibitors of apoptosis as well as genes involved in homologous repair warrants combination studies with drugs that target these proteins, to overcome resistance to oxaliplatin and other platinum drugs.

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