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Anti-cancer effects of artemesunate in a panel of chemoresistant neuroblastoma cell lines

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1. Introduction

Neuroblastoma is the most frequent extracranial solid tumour of childhood. About half of all neuroblastoma patients are diagnosed with high-risk disease characterised by overall survival rates below 40% despite intensive multimodal treatment [1]. Therapy failure is basically caused by acquired chemoresistance [2].

Artemisinin derivatives including artemisinin, dihydroartemisinin, and artemesunate are well-tolerated anti-malaria drugs that also exert anti-cancer activity. Here, we investigated artemisinin and its derivatives dihydroartemisinin and artemesunate in a panel of chemosensitive and chemoresistant human neuroblastoma cells as well as in primary neuroblastoma cultures. Only dihydroartemisinin and artemesunate affected neuroblastoma cell viability with artemesunate being more active. Artesunate-induced apoptosis and reactive oxygen species in neuroblastoma cells. Of 16 cell lines and two primary cultures, only UKF-NB-3'CDDP1000 showed low sensitivity to artemesunate. Characteristic gene expression signatures based on a previous analysis of artemesunate resistance in the NCI60 cell line panel clearly separated UKF-NB-3'CDDP1000 from the other cell lines. L-Buthionine-S,R-sulfoximine, an inhibitor of GCL (glutamate–cysteine ligase), resensitised in part UKF-NB-3'CDDP1000 cells to artemesunate. This finding together with bioinformatic analysis of expression of genes involved in glutathione metabolism showed that this pathway is involved in artemesunate resistance. These data indicate that neuroblastoma represents an artemesunate-sensitive cancer entity and that artemesunate is also effective in chemoresistant neuroblastoma cells.

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ABSTRACT

Artemisinin derivatives are well-tolerated anti-malaria drugs that also exert anti-cancer activity. Here, we investigated artemisinin and its derivatives dihydroartemisinin and artemesunate in a panel of chemosensitive and chemoresistant human neuroblastoma cells as well as in primary neuroblastoma cultures. Only dihydroartemisinin and artemesunate affected neuroblastoma cell viability with artemesunate being more active. Artesunate-induced apoptosis and reactive oxygen species in neuroblastoma cells. Of 16 cell lines and two primary cultures, only UKF-NB-3'CDDP1000 showed low sensitivity to artemesunate. Characteristic gene expression signatures based on a previous analysis of artemesunate resistance in the NCI60 cell line panel clearly separated UKF-NB-3'CDDP1000 from the other cell lines. L-Buthionine-S,R-sulfoximine, an inhibitor of GCL (glutamate–cysteine ligase), resensitised in part UKF-NB-3'CDDP1000 cells to artemesunate. This finding together with bioinformatic analysis of expression of genes involved in glutathione metabolism showed that this pathway is involved in artemesunate resistance. These data indicate that neuroblastoma represents an artemesunate-sensitive cancer entity and that artemesunate is also effective in chemoresistant neuroblastoma cells.

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2. Materials and methods

2.1. Cells

The cell lines UKF-NB-3 and UKF-NB-6 were isolated from bone marrow metastases of N-myc-amplified stage 4 neuroblastoma patients [15, 20]. IMR-32 cells were obtained from ATCC (Manassas, VA, USA). The parental UKF-NB-3, UKF-NB-6 or IMR-32 cells are chemosensitive (no P-gp expression, wild-type p53) [15, 17, 20]. Cells were adapted to growth in the presence of vincristine (VCR, obtained from GRY Pharma GmbH, Kirchzarten, Germany), doxorubicin (DOX, obtained from medac Gesellschaft für klinische Spezialpräparate mbH, Hamburg, Germany), cisplatin (CDDP, obtained from GRY Pharma GmbH, Kirchzarten, Germany), melphalan (MEL, obtained from GlaxoSmithKline GmbH & Co. KG, Munich, Germany), etoposide (ETO, obtained from GRY Pharma GmbH, Kirchzarten, Germany), or topotecan (TOP, obtained from GlaxoSmithKline GmbH & Co. KG, Munich, Germany) by described methods and named following the published nomenclature [14, 15], i.e., UKF-NB-3VCR10 means UKF-NB-3 adapted to vincristine 10 ng/mL, UKF-NB-3DOX20 means UKF-NB-3 adapted to doxorubicin 20 ng/mL, UKF-NB-3CDDP1000 means UKF-NB-3 adapted to cisplatin 1000 ng/mL. All cell lines were grown in IMDM supplemented with 10% FCS, 100 IU/ml penicillin, and 100 mg/ml streptomycin at 37 °C.

Fresh neuroblastoma cells (MYCN amplified) were isolated from the bone marrow aspirate of two patients with metastasised INSS stage 4 neuroblastoma following informed consent. Primary cells were cultivated in IMDM supplemented with 10% FCS, 100 IU/ml penicillin, and 100 mg/ml streptomycin at 37 °C.

2.2. Viability assay

Viability of cells from cancer cell lines was investigated using the 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT) dye reduction assay as described before [16]. Viability of primary neuroblastoma cells was examined by the CellTiter-Glo® Luminescent Cell Viability Assay (Promega, Mannheim, Germany) following the manufacturer’s instructions.

2.3. Apoptosis

Activated caspase-3 was detected by immune staining. The primary antibody was: caspase-3 (active) (R&D Systems, Wiesbaden, Germany). Biotin-conjugated secondary monoclonal antibodies were used and visualisation was performed with streptavidin–peroxidase complex with AEC (3-amino-9-ethylcarbazole, purchased from Sigma–Aldrich Chemie GmbH, Munich, Germany) and analysed by flow cytometry (FacsCalibur, BD Biosciences, Heidelberg, Germany).

In addition to staining for activated caspase-3, apoptotic cells were detected as the cells with fractional DNA content (“sub-G1” cell subpopulation). Cells were fixed with 70% ethanol for 2 h at −20 °C. The cellular DNA was stained using propidium iodide (20 μg/mL, purchased from Sigma–Aldrich Chemie GmbH, Munich, Germany) and analysed by flow cytometry (FacsCalibur, BD Biosciences, Heidelberg, Germany).

2.4. Determination of cellular oxidative stress

Reactive oxygen species (ROS) were detected in artesunate-treated cells using the Image-iT LIVE Green Reactive Oxygen Species Kit (Molecular Probes, distributed by Invitrogen, Karlsruhe, Germany).

2.5. Gene expression analysis

Gene expression analysis using AB1700 Human Genome Survey Microarray V2.0 chips (Applied Biosystems, Darmstadt, Germany) was performed by IMGM laboratories (Martinsried, Germany) for the cell lines UKF-NB-3, UKF-NB-3VCR10, UKF-NB-3CDDP1000, UKF-NB-6, UKF-NB-6VCR10, or UKF-NB-6CDDP1000. mRNA was isolated using the RNeasy kit (Qiagen, Hilden, Germany) according to the manufacturer’s instructions. Experiments were performed in triplicates.

Expression data were processed using the R/bioconductor package ‘Affyarray’ (http://www.r-project.org; http://www.bioconductor.org/) with default parameters (SN threshold ≥ 3, %detect samples: 0.5). This included quality control, quantile normalisation [21], and filtering of unspecific hybridisation.

For every microarray experiment, the expression pattern of 50 randomly chosen genes was verified by quantitative real-time PCR resulting in confirmation of expression of >80% of investigated genes (data not shown).

Cluster analysis was performed using Euclidean distance and complete linkage and was visualised as heatmap. All steps were processed in R (www.r-project.org; Kendall’s τ-test, clustering and heatmaps were based on the package stats; correction for multiple testing was performed with multitest).

3. Results

3.1. Sensitivity of neuroblastoma cells to artemisinin derivatives

The IC50-values for the effects of artemisinin, dihydroartemisinin, or artesunate on the viability of the investigated neuroblastoma cell lines are shown in Table 1. Artemisinin concentrations of 50 μM failed to reduce the viability of neuroblastoma cells by 50%. The IC50-values for dihydroartemisinin and artesunate ranged from 1.43 to 11.95 μM whereas IC50-values for most cell lines were below 5 μM. The only exception was the cell line UKF-NB-3CDDP1000 for which the IC50-values were 24.9 ± 0.28 μM for dihydroartemisinin and 29.7 ± 0.35 μM for artesunate.

In addition to testing in neuroblastoma cell lines, artemisinin, dihydroartemisinin, and artesunate were investigated in primary neuroblastoma cells isolated from the bone marrow of two patients with metastasised INSS stage 4 neuroblastoma (Table 2). IC50-values for dihydroartemisinin and artesunate were below 10 μM and IC50-values for artesunate were >50 μM.

Since dihydroartemisinin and artesunate exerted similar anti-neuroblastoma effects and the IC50-values for artesunate were in general lower, subsequent experiments were performed with artesunate.

3.2. Artesunate induces apoptosis in neuroblastoma cell lines

To investigate if artesunate induces apoptosis in neuroblastoma cells, the parental chemosensitive UKF-NB-3 cell line and its chemoresistant sub-lines were investigated for caspase-3 activation and cells in sub-G1 phase. Artesunate 10 μM treatment for 24 h resulted in a significant increase of cells positively stained for fragmented DNA content (Fig. 1A). Forty-eight hour-treatment of neuroblastoma cells with artesunate 10 μM significantly enhanced the number of cells in sub-G1 phase (Fig. 1B).

3.3. Determination of cross-resistance profiles in the cell line UKF-NB-3 and its chemoresistant sub-lines

The cytotoxic mechanism of action of artesunate was suggested to differ from the mechanisms of established anti-cancer drugs
Cross-resistance profiles were determined in a cell line panel consisting of the parental chemosensitive neuroblastoma cell line UKF-NB-3 and its sub-lines adapted to the cytotoxic drugs vincristine (UKF-NB-3rVCR100), doxorubicin (UKF-NB-3rDOX20), cisplatin (UKF-NB-3rCDDP1000), topotecan (UKF-NB-3rTOP15), melphalan (UKF-NB-3rMEL2000), or etoposide (UKF-NB-3rETO100). IC50 values were determined for each drug used for adaptation (Table 3). Moreover, relative cellular resistances (IC50 chemoresistant UKF-NB-3 sub-line/IC50 UKF-NB-3) indicating resistance/sensitivity of chemoresistant sub-lines to each drug relative to parental chemosensitive UKF-NB-3 cells were calculated for each cytotoxic drug (Table 3). In general, adaptation of UKF-NB-3 cells to one cytotoxic drug resulted in decreased sensitivity to the whole panel of anti-cancer drugs. In contrast, drug-resistant UKF-NB-3 sub-lines showed comparable or increased sensitivity to artesunate (with the exception of UKF-NB-3rCDDP1000).

### 3.4. Investigation of neuroblastoma cells for gene expression signatures that predict cancer cell response to artesunate

Gene expression signatures that correlated with cancer cell sensitivity to artesunate had been established before by correlation of gene expression with IC50 levels of artesunate in 55 cell lines from the NCI60 panel using Kendall’s ρ-test ([9,10,22,23]). From these signatures, we created a list of 94 genes for which expression has been shown to directly or inversely correlate to artesunate resistance in the cells from the NCI60 panel (Appendix Supplementary Table 1). Cluster analysis of the cell lines UKF-NB-3, UKF-NB-3rVCR100, UKF-NB-3rCDDP1000, UKF-NB-6, UKF-NB-6rVCR100, and UKF-NB-6rCDDP1000 for expression of these genes could clearly differentiate the artesunate-resistant UKF-NB-3rCDDP1000 cell line from the other cell lines showing substantially higher artesunate sensitivity (Fig. 2).

**Table 1**

<table>
<thead>
<tr>
<th>Cell line</th>
<th>IC50 (µM)</th>
<th>Artemisinin</th>
<th>Dihydroartemisinin</th>
<th>Artesunate</th>
</tr>
</thead>
<tbody>
<tr>
<td>UKF-NB-3</td>
<td>&gt;50</td>
<td>4.50 ± 0.30</td>
<td>2.69 ± 0.10</td>
<td></td>
</tr>
<tr>
<td>UKF-NB-3rVCR100</td>
<td>&gt;50</td>
<td>2.09 ± 0.20</td>
<td>1.43 ± 0.12</td>
<td></td>
</tr>
<tr>
<td>UKF-NB-3rDOX20</td>
<td>&gt;50</td>
<td>3.18 ± 0.50</td>
<td>2.24 ± 0.06</td>
<td></td>
</tr>
<tr>
<td>UKF-NB-3rCDDP1000</td>
<td>&gt;50</td>
<td>24.9 ± 0.28</td>
<td>29.70 ± 0.35</td>
<td></td>
</tr>
<tr>
<td>UKF-NB-3rTOP15</td>
<td>&gt;50</td>
<td>2.24 ± 0.08</td>
<td>1.93 ± 0.20</td>
<td></td>
</tr>
<tr>
<td>UKF-NB-3rMEL2000</td>
<td>&gt;50</td>
<td>2.85 ± 0.08</td>
<td>1.62 ± 0.40</td>
<td></td>
</tr>
<tr>
<td>UKF-NB-3rETO100</td>
<td>&gt;50</td>
<td>3.90 ± 0.13</td>
<td>2.53 ± 0.50</td>
<td></td>
</tr>
<tr>
<td>UKF-NB-6</td>
<td>&gt;50</td>
<td>6.24 ± 0.19</td>
<td>3.54 ± 0.42</td>
<td></td>
</tr>
<tr>
<td>UKF-NB-6rVCR10</td>
<td>&gt;50</td>
<td>11.05 ± 0.20</td>
<td>7.13 ± 0.17</td>
<td></td>
</tr>
<tr>
<td>UKF-NB-6rDOX20</td>
<td>&gt;50</td>
<td>7.30 ± 0.14</td>
<td>9.90 ± 1.20</td>
<td></td>
</tr>
<tr>
<td>UKF-NB-6rCDDP1000</td>
<td>&gt;50</td>
<td>6.67 ± 0.10</td>
<td>2.27 ± 0.06</td>
<td></td>
</tr>
<tr>
<td>UKF-NB-6rTOP15</td>
<td>&gt;50</td>
<td>5.35 ± 0.48</td>
<td>3.72 ± 0.20</td>
<td></td>
</tr>
<tr>
<td>IMR-32</td>
<td>&gt;50</td>
<td>3.15 ± 0.16</td>
<td>2.69 ± 0.18</td>
<td></td>
</tr>
<tr>
<td>IMR-32rDOX20</td>
<td>&gt;50</td>
<td>3.69 ± 0.13</td>
<td>3.80 ± 0.90</td>
<td></td>
</tr>
<tr>
<td>IMR-32rCDDP1000</td>
<td>&gt;50</td>
<td>4.03 ± 0.23</td>
<td>3.05 ± 0.37</td>
<td></td>
</tr>
<tr>
<td>IMR-32rMEL2000</td>
<td>&gt;50</td>
<td>2.46 ± 0.15</td>
<td>2.40 ± 0.23</td>
<td></td>
</tr>
</tbody>
</table>

**Table 2**

<table>
<thead>
<tr>
<th>IC50 (µM)</th>
<th>Patient 1</th>
<th>Patient 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Artemisinin</td>
<td>8.30 ± 2.95</td>
<td>6.58 ± 2.72</td>
</tr>
<tr>
<td>Dihydroartemisinin</td>
<td>6.69 ± 2.28</td>
<td>5.11 ± 2.61</td>
</tr>
<tr>
<td>Artesunate</td>
<td>5.00 ± 0.04</td>
<td>4.20 ± 0.12</td>
</tr>
</tbody>
</table>

For eight genes of the 94 gene list, a statistically significant correlation between gene expression and the IC50 for artesunate was detected in our cell lines (Appendix Supplementary Table 1). For five of these eight genes, the correlation was found to be of the same type (direct or inverse) as determined in the previous works [9,10,22,23]. The expression of the remaining three genes was correlated to the artesunate IC50 in the opposite direction (Appendix Supplementary Table 1).

### 3.5. Sensitisation of UKF-NB-3rCDDP1000 cells to artesunate by l-buthionine-S,R-sulfoximine (BSO)

l-Buthionine-S,R-sulfoximine (BSO) is a glutathione-depleting agent that inhibits GCL (glutamate–cysteine ligase, also known as γ-glutamylcysteine synthetase), which has been shown to sensitise artesunate-resistant cells to artesunate [22]. Moreover, GCL transfection decreased the cancer cell sensitivity to artesunate [10,22]. GCL catalyses the first and rate-limiting step in the cellular synthesis of glutathione. The enzyme is encoded by two different genes, GCLC for the catalytic subunit, GCLM for a modulatory subunit. Only the gene product of GCLC is regarded to be essential for GCL function [24–29].
In UKF-NB-3rCDDP1000 cells GCLC expression was found to be significantly higher than in UKF-NB-3 cells while GCLM expression did not differ between these cell lines (Supplimentary Table 2). Treatment of UKF-NB-3rCDDP1000 cells with a fixed BSO concentration (50 μM) that did not affect cell viability (92.61 ± 6.77% relative to non-treated control) resulted in a 4.6-fold decrease of the IC50 for artesunate (IC50 with BSO: 6.48 ± 2.18 μM; IC50 without BSO 29.70 ± 0.35 μM). However, the IC50-value remained clearly (2.41-fold) higher than that detected in artesunate-treated UKF-NB-3 cells (2.69 ± 0.10 μM).

Different glutathione-related enzymes had been shown to contribute to resistance to artesunate [22]. Hierarchical clustering of the expression of glutathione-related enzymes that had been suggested before to be correlated to artesunate sensitivity/resistance [22] (Table S2) distinguished between low artesunate-sensitive UKF-NB-3rCDDP1000 cells and the more sensitive cell lines (Fig. 3).

The anti-cancer mechanism of action of artesunate is suspected to include induction of oxidative stress by cleavage of its endoperoxide moiety catalysed by Fe2+ ions [3,30]. Since BSO partly sensitised UKF-NB-3rCDDP1000 cells to artesunate and the

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**Table 3**

<table>
<thead>
<tr>
<th>Cell line</th>
<th>Drug sensitivity (IC50 (ng/ml))/relative resistance (IC50 UKF-NB-3 sub-line/IC50 UKF-NB-3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vincristin</td>
<td>Drug sensitivity (IC50 (ng/ml))/relative resistance (IC50 UKF-NB-3 sub-line/IC50 UKF-NB-3)</td>
</tr>
<tr>
<td>Doxorubicin</td>
<td>Drug sensitivity (IC50 (ng/ml))/relative resistance (IC50 UKF-NB-3 sub-line/IC50 UKF-NB-3)</td>
</tr>
<tr>
<td>Cisplatin</td>
<td>Drug sensitivity (IC50 (ng/ml))/relative resistance (IC50 UKF-NB-3 sub-line/IC50 UKF-NB-3)</td>
</tr>
<tr>
<td>Topotecan</td>
<td>Drug sensitivity (IC50 (ng/ml))/relative resistance (IC50 UKF-NB-3 sub-line/IC50 UKF-NB-3)</td>
</tr>
<tr>
<td>Melphalan</td>
<td>Drug sensitivity (IC50 (ng/ml))/relative resistance (IC50 UKF-NB-3 sub-line/IC50 UKF-NB-3)</td>
</tr>
<tr>
<td>Etoposide</td>
<td>Drug sensitivity (IC50 (ng/ml))/relative resistance (IC50 UKF-NB-3 sub-line/IC50 UKF-NB-3)</td>
</tr>
<tr>
<td>Artesunate</td>
<td>Drug sensitivity (IC50 (ng/ml))/relative resistance (IC50 UKF-NB-3 sub-line/IC50 UKF-NB-3)</td>
</tr>
</tbody>
</table>

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Fig. 2. Hierarchical cluster analysis and heatmap of expression of genes reported to be involved in cancer cell sensitivity to artesunate [9,10,21,22] in the cell lines UKF-NB-3 (two independent experiments were performed for the comparison of parental and chemoresistant cells; UKF-NB-3* corresponds to gene expression profiles determined together with UKF-NB-3rVCR10, UKF-NB-3 to gene expression profiles determined together with UKF-NB-3rCDDP1000 cells), UKF-NB-3rVCR10, UKF-NB-3rCDDP1000, UKF-NB-6 (UKF-NB-6* corresponds to gene expression profiles determined together with UKF-NB-6rVCR10, UKF-NB-6 to gene expression profiles determined together with UKF-NB-6rCDDP1000 cells), UKF-NB-6rVCR10, or UKF-NB-6rCDDP1000.

---

Fig. 3. Hierarchical cluster analysis and heatmap of expression of genes encoding for glutathione-related enzymes reported to be involved in cancer cell sensitivity to artesunate [21] in the cell lines UKF-NB-3 (two independent experiments were performed for the comparison of parental and chemoresistant cells; UKF-NB-3* corresponds to gene expression profiles determined together with UKF-NB-3rVCR10, UKF-NB-3 to gene expression profiles determined together with UKF-NB-3rCDDP1000 cells), UKF-NB-3rVCR10, UKF-NB-3rCDDP1000, UKF-NB-6 (UKF-NB-6* corresponds to gene expression profiles determined together with UKF-NB-6rVCR10, UKF-NB-6 to gene expression profiles determined together with UKF-NB-6rCDDP1000 cells), UKF-NB-6rVCR10, or UKF-NB-6rCDDP1000.
glutathione metabolism is known to be involved in the cellular response to oxidative stress [31,32]. UKF-NB-3 or UKF-NB-3\(^{3'\text{CDDP}}\) were treated for 24 h with different concentrations of artesunate and the cellular formation of reactive oxygen species (ROS) was measured. Artesunate-induced in both cell lines oxidative stress in a concentration-dependent manner, however, ROS production was much more pronounced in UKF-NB-3 cells, especially in lower artesunate concentrations (Fig. 4).

4. Discussion

Artemisinin and its derivatives dihydroartemisinin and arte-
sunate were investigated for anti-neuroblastoma activity in a panel of chemosensitive and chemoresistant neuroblastoma cell lines. While artemisinin was not effective in concentrations up to 50 \(\mu\)M, dihydroartemisinin and artesunate exerted anti-cancer effects in concentrations between 1.43 and 11.95 \(\mu\)M (with the exception of UKF-NB-3\(^{3'\text{CDDP}}\)): IC\(_{50}\) artesunate 29.7 \(\mu\)M; IC\(_{50}\) dihydroartemisinin 24.9 \(\mu\)M. In the UKF-NB-3 cell line and its chemoresistant sub-lines, the artesunate-induced decrease in neuroblastoma cell viability was paralleled by increased numbers of cells stained positively for activated caspase-3 or enhanced numbers of cells in sub-G1 phase indicating apoptosis induction. In addition to examination of cell lines, the substances were tested in primary cultures obtained from two patients with metastasised INSS stage 4 neuroblastoma with similar results. The investigated artesunate concentrations are in the range of those found effective in melanoma cell lines [9] and about 1000-fold lower than peak plasma levels determined in malaria patients that were reported to be 6.88±4.69 mM after i.v. administration of artesunate 2 mg/kg [33]. Notably, two melanoma patients showed favourable response to artesunate treatment [3].

As shown by the determination of cross-resistance profiles established for the parental chemosensitive cell line UKF-NB-3 and its sub-lines adapted to various cytotoxic drugs, adaptation of UKF-
NB-3 cells to one cytotoxic drug usually decreased its sensitivity to the whole panel of structurally different anti-cancer including vincristine (interferes with formation of the spindle apparatus), doxorubicin (intercalating agent, inhibits topoisomerase II), cisplatin (DNA crosslinker), topotecan (inhibits topoisomerase I), melphalan (alkylating agent), etoposide (inhibits topoisomerase II). In clear contrast, only one of the chemoresistant sub-lines of UKF-NB-3 (UKF-NB-3\(^{3'\text{CDDP}}\)) showed a profound decreased sensitivity to artesunate relative to the sensitivity of the parental chemosensitive cell line. This supports previous findings suggesting that artesunate differs in its anti-cancer mechanism from that of other cytotoxic drugs [3,9,10]. Most recently, artesunate was found to target topoisomerase II\(\alpha\) with a similar potency like etoposide [11]. Notably, artesunate was similar effective in parental UKF-NB-3 cells (IC\(_{50}\) = 2.69 ± 0.10) and in the sub-line resistant to the topoisomerase II\(\alpha\) inhibitor etoposide UKF-NB-
3\(^{3'\text{ETO}}\) (IC\(_{50}\) = 2.53 ± 0.50). Moreover, different chemoresistance mechanisms including overexpression of the ABC transporter P-glycoprotein and p53 inactivation did not attenuate cancer cell sensitivity to artesunate in previous studies [3,12,13]. In accordance, neuroblastoma cells that overexpress P-glycoprotein (e.g., UKF-NB-
3\(^{3'DOX}\), UKF-NB-6\(^{VCR}\), UKF-NB-6\(^{DOX}\)) [15,20] and those that harbour a loss-of-function p53 mutation in addition to P-glycoprotein expression (UKF-NB-3\(^{3'\text{VCR}}\)) [15,19] were similarly sensitive to artesunate like chemosensitive parental neuroblastoma cells. The anti-cancer mechanism of artesunate is suspected to include induction of oxidative stress by cleavage of its endoperoxide moiety catalysed by Fe\(^{2+}\) ions [3,30,34]. In concordance, increased expression of genes encoding for anti-oxidative gene products including DHDH (encoding for dihydrodihydrogenase), GCLC/GCLM (encoding for GCL), GSTM4, GSTT2, GSTZ1 (all encoding for glutathione S-transferases), and MGST3 (encoding for microsomal glutathione S-transferase 3) have been found to correlate with cancer cell resistance to artesunate [9,10] and the GCL inhibitor BSO that depletes cellular glutathione pools sensitised cancer cells to artesunate [22]. Moreover, GCL transfection decreased the cellular sensitivity to artesunate [10,22].

Anti-oxidative gene expression has also been reported to contribute to cisplatin resistance [35–37]. Intracellularly, the cis-
chloro ligands of cisplatin are displaced by water molecules resulting in a complex that reacts with nucleophilic centres of biomolecules including DNA, RNA, proteins, and membrane phospholipids. Thereby, the formation of inter- and intra-strand DNA cross-links is regarded to be critical for the anti-cancer and pro-apoptotic activity of cisplatin [35,38]. Moreover, cisplatin-induced ROS induction has been found to contribute to the pro-apoptotic activity of cisplatin [39–42] and anti-oxidative gene expression contributes to cancer cell resistance to cisplatin by interfering with DNA binding as well as by antagonising ROS formation [35–37,39–44].

Artesunate-induced ROS formation was strongly decreased in the artesunate-resistant UKF-NB-3\(^{3'\text{CDDP}}\) cell line in comparison to the sensitive parental cell line UKF-NB-3. GCL catalyses the first and rate-limiting step in the cellular synthesis of the tripeptide glutathione (\(\gamma\)-glutamylcysteinylglycine). The enzyme is encoded by two different genes. GCLC encodes for the catalytic subunit. GCLM encodes for a modulatory subunit. The gene product of GCLM is regarded to be essential for GCL function and homozygous GCLC knock-out mice were not viable. The gene product of GCLM increases the affinity of the catalytic subunit for glutamate and decreases the sensitivity to feedback inhibition by glutathione but appears not to be essential for enzyme function since homozygous GCLM knock-out mice are
viable and fertile [24–29]. The artesunate-resistant UKF-NB-3’CDDP1000 cell line showed increased expression of GCLC but not of GCLM. BSO increased the artesunate sensitivity of UKF-NB-3’CDDP1000 cells but the artesunate IC50-value remained clearly higher than that determined in the parental chemosensitive UKF-NB-3 cell line. Notably, a signature of genes encoding for glutathione-related enzymes that were suggested before to be involved in artesunate resistance [22] distinguished between UKF-NB-3’CDDP1000 and the more artesunate-sensitive cell lines (Fig. 3).

Moreover, a 94-gene list assembled from different previous studies that reported on the correlation of gene expression data from the NCI60 panel to the artesunate IC50-values in these cells [9,10,22,23] separated UKF-NB-3’CDDP1000 from the more artesunate-sensitive cell lines (Fig. 2). This agreement between our data and the previous expression signature is striking, given the tremendous heterogeneity even of cancers from related entities [45,46] and the fact that no neuroblastoma cell lines are included in the NCI60 cell line panel. The finding that gene expression signatures derived from the NCI60 panel is suited to differentiate between artesunate-sensitive and resistant neuroblastoma cell lines illustrates the general applicability of pharmacogenomic approaches.

In conclusion, our data show that artesunate is effective in the majority of the investigated chemosensitive and chemoresistant neuroblastoma cell lines and in primary neuroblastoma cell cultures. The anti-cancer mechanism of artesunate differs from that of established anti-cancer drugs and involves induction of oxidative stress. Gene expression signatures derived from previous investigations using cells from other entities than neuroblastoma were able to discriminate between the artesunate-resistant UKF-NB-3’CDDP1000 cell line and the more sensitive neuroblastoma cell lines investigated. Since clinical studies investigating artesunate for malaria treatment revealed that the drug is very well-tolerated in children and that side-effects are low [47–49] and neuroblastoma is a neoplasm of early childhood (96% of cases occur before the age of 10 years [2]), our findings warrant the further investigation of artesunate as anti-neuroblastoma drug.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.bcp.2009.08.013.

References