Mitotane alters mitochondrial respiratory chain activity by inducing cytochrome c oxidase defect in human adrenocortical cells

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Abstract

Mitotane, 1,1-dichloro-2-(o-chlorophenyl)-2-(p-chlorophenyl)ethane is the most effective medical therapy for adrenocortical carcinoma, but its molecular mechanism of action remains poorly understood. Although mitotane is known to have mitochondrial (mt) effects, a direct link to mt dysfunction has never been established. We examined the functional consequences of mitotane exposure on proliferation, steroidogenesis, and mt respiratory chain, biogenesis and morphology, in two human adrenocortical cell lines, the steroid-secreting H295R line and the non-secreting SW13 line. Mitotane inhibited cell proliferation in a dose- and a time-dependent manner. At the concentration of 50 μM (14 mg/l), which corresponds to the threshold for therapeutic efficacy, mitotane drastically reduced cortisol and 17-hydroxyprogesterone secretions by 70%. This was accompanied by significant decreases in the expression of genes encoding mt proteins involved in steroidogenesis (STAR, CYP11B1, and CYP11B2). In both H295R and SW13 cells, 50 μM mitotane significantly inhibited (50%) the maximum velocity of the activity of the respiratory chain complex IV (cytochrome c oxidase (COX)). This effect was associated with a drastic reduction in steady-state levels of the whole COX complex as revealed by blue native PAGE and reduced mRNA expression of both mtDNA-encoded COX2 (MT-CO2) and nuclear DNA-encoded COX4 (COX4I1) subunits. In contrast, the activity and expression of respiratory chain complexes II and III were unaffected by mitotane treatment. Lastly, mitotane exposure enhanced mt biogenesis (increase in mtDNA content and PGC1α (PPARGC1A) expression) and triggered fragmentation of the mt network. Altogether, our results provide first evidence that mitotane induced a mt respiratory chain defect in human adrenocortical cells.

Key Words

- adrenocortical carcinoma
- mitotane
- o,p’-DDD
- mitochondria
- cytochrome c oxidase
Introduction

Adrenocortical carcinoma (ACC) is a rare disease affecting two patients per million people per year, representing <0.1% of all cancer cases. ACC prognosis is poor with <15% of patients surviving 5 years or more once metastases are diagnosed (Icard et al. 2001, Assie et al. 2007, Fassnacht & Alloino 2009, Lughezzani et al. 2010).

Mitotane, 1,1-dichloro-2-[(o-chlorophenyl)-2-[(p-chlorophenyl)ethane (o,p'-DDD), is a synthetic derivative of an insecticide. It acts selectively on the adrenal cortex where it has a cytotoxic effect and impairs steroidogenesis (Bergenstal & Dao 1953). Mitotane is a part of the reference treatment of advanced ACC (Berruti 2012, Fassnacht et al. 2012). Indeed, it remains the single most effective drug, inducing a partial response in up to one third of the treated patients (Baudin et al. 2011). Several retrospective studies have shown that plasma mitotane levels above 14 mg/l are associated with a higher partial response rate and improve overall survival (Haak et al. 1994, Baudin et al. 2001, Malandrino et al. 2010, Wangberg et al. 2010, Hermse et al. 2011). The current recommendation to achieve optimal benefit over risk ratio in patients with unresectable ACC is to maintain plasma mitotane levels between 14 and 20 mg/l (Berruti 2012).

Mitotane’s molecular mechanisms of action remain largely unknown, although mitochondrial (mt) effects have been reported. Kaminsky et al. (1962) observed swollen mitochondria in the adrenal cortex of mitotane-treated dogs by electron microscopy. Subsequently, Martz & Straw (1977) suggested that metabolic transformation of o,p'-DDD into the active metabolite o,p'-DDA occurs in mitochondria and is catalyzed by an unknown cytochrome P450. Mitotane metabolism seems to involve two successive reactions of β-hydroxylation and dehydrochlorination, leading to production of free radicals that could potentially result in apoptosis (Cai et al. 1995). Critical steps of mitotane’s inhibitory effects on steroidogenesis may occur in mitochondria possibly involving CYP11A1, a mt enzyme that catalyzes the transformation of cholesterol to pregnenolone (Cai et al. 1997). Elevated levels of 11-deoxycortisol and 11-deoxycorticosterone in mitotane-treated patients suggest that mitotane may affect CYP11B1, which is responsible for cortisol synthesis (Asp et al. 2012). More recently, Stigliano et al. (2008) showed by proteomic analysis of H295R cells that expression of proteins involved in stress response, energy metabolism, and tumorigenesis was greatly altered by mitotane exposure. Interestingly, some of these regulated proteins were mt components, even though a direct impact on their synthesis and/or stability has not been clearly demonstrated. The functional consequences of mitotane on respiratory chain expression and activity have not yet been examined. The respiratory chain consists of four multienzymatic complexes located in the mt inner membrane. Together with the ATP synthase complex, it performs an essential mt function, generating the vast majority of cellular ATP synthesis, while reducing molecular oxygen into water. It is a major source of free radicals in most cells and its function is tightly linked to apoptosis balance. The respiratory chain has been shown to be the target of several pharmacological compounds including non-steroidal anti-inflammatory drugs, antiretrovirals, and chemotherapy agents (Viengchareun et al. 2007, Fedeles et al. 2011, Scatena 2012).

The aim of this study was to evaluate the functional consequences of mitotane exposure on mt oxidative phosphorylation (OXPHOS) in human adrenocortical steroid-secreting H295R and non-secreting SW13 cells, both derived from human ACC. We used complementary experimental approaches including spectrophotometric assays, western blot, quantitative PCR, and mt morphological analysis to explore how mitotane affects mediators of steroidogenesis and respiratory chain activity.

Materials and methods

Cell culture and treatment

H295R and SW13 cells were cultured in DMEM/HAM’S F-12 (PAA, Les Mureaux, France) supplemented with 20 mM HEPES (Invitrogen, Life Technologies), antibiotics (penicillin 100 IU/ml and streptomycin 100 μg/ml), and 2 mM glutamine. The medium for H295R cell culture was enriched with 10% fetal bovine serum and a mixture of insulin/transferrin/selenium. Both cell lines (from passages 2–15) were cultured at 37 °C in a humidified incubator with 5% CO₂. Mitotane (supplied by HRA Pharma, Paris, France) dissolved in DMSO was added to cell cultures at final concentrations of 10–100 μM; the therapeutic plasma mitotane level is 50 μM (approximately 14 mg/l).

Cell proliferation analysis

Cell proliferation was studied in Celltiter 96 assays (Promega) according to the manufacturer’s recommendations. Cells were cultured in 96-well plates and treated...
with 10–100 µM mitotane for 24, 48, or 72 h. Absorbance was measured by photometry (Viktor, Perkin Elmer, Courtaboeuf, France) 1 h after addition of 20 µl Celltiter solution per well.

Cortisol and 17-hydroxyprogesterone secretion

The cortisol and 17-hydroxyprogesterone (17-OH-progesterone) concentrations in H295R culture supernatants were determined by radioimmunounometric assays using polyclonal antibodies (anti-cortisol: Orion Diagnostica, Spectria, Espoo, Finland; anti-17-OH-progesterone: MP Biomedical, Solon, OH, USA). The intra- and interassay coefficients of variation of the cortisol were respectively 4.5 and 5.5% at 22 µg/l, and 4.2 and 4.3% at 269 µg/l, with a detection limit of 5 µg/l while those of the 17-OH-progesterone assay were 7.8 and 12% at 0.92 ng/ml, and 8.3 and 9.8% at 4.3 ng/ml with a detection limit of 0.02 ng/ml.

Reverse transcriptase-PCR and quantitative real-time PCR

Total RNA was extracted from tissues or cells with the RNaseasy Kit (Qiagen) according to the manufacturer’s recommendations. RNA was thereafter processed for reverse transcriptase-PCR (RT-PCR) as described previously (Martinerie et al. 2011). Quantitative real-time PCR (qRT-PCR) was performed using the Fast SYBR Green Master Mix (ABI, Applied Biosystems) and carried out on a StepOnePlus Real-Time PCR System (Applied Biosystems) as described previously (Martinerie et al. 2011). Standards and samples were amplified in duplicate and analyzed from three independent experiments. The internal control for data normalization was the ribosomal 18S rRNA. The relative expression of each gene is expressed as the ratio of attomoles of the specific gene to femtomoles of 18S rRNA. The primer sequences of the genes analyzed by qRT-PCR are shown in the Supplementary Table 1, see section on supplementary data given at the end of this article.

mtDNA quantification

mtDNA quantification was performed on total DNA extracted from tissues or cells using standard techniques. DNA was quantified by qPCR using the cytochrome c oxidase 2 (COX2 (MT-CO2)) gene on the mtDNA as a target gene as described previously (Viengchareun et al. 2007). Results were expressed as relative expression of COX2 normalized with the nuclear 18S gene.

Respiratory chain analysis

Respiratory chain activities were measured using spectrophotometric assays. H295R and SW13 cells were treated with mitotane or vehicle (DMSO) alone for various periods, 24, 48, or 72 h, and the activity of four mt respiratory complexes – complex I (NADH–ubiquinone oxidoreductase), complex II (succinate–ubiquinone oxidoreductase), complex III (ubiquinone–cytochrome c oxidoreductase), and complex IV (COX) – were measured in a Cary 50 Spectrophotometer (Rustin et al. 1994). Assays of complexes II, III, and IV were performed on cell homogenates, and their activities normalized to citrate synthase activity, as an index of mt mass. Complex I assays were performed on purified mt fractions and prepared from permeabilized cells as described previously (Chretien et al. 2003).

BN-PAGE analysis

Mitochondria and OXPHOS complexes were isolated from cultured cells using 2% (W/V) digitonin and analyzed as described (Nijtmans et al. 2002a,b). Fifteen micrograms of solubilized OXPHOS proteins were loaded on a 4–16% gradient acrylamide non-denaturing gel (Invitrogen). After electrophoresis, proteins were transferred to a PVDF membrane. Immunoblotting was performed with MABs (Mitosciences, Mundolsheim, France) raised against the complex I subunit GRIM19, the 70 kDa complex II subunit, the complex III subunit core2, and the complex IV subunit COX1. Peroxidase-conjugated anti-mouse IgG secondary antibodies were added and the signal was generated using ECL (Pierce, Rockford, IL, USA). Membranes were scanned using the Odyssey infrared imaging system and images were processed with the Image Studio Software (LI-COR Biosciences, Lincoln, NE, USA).

mt morphology

Cells were seeded at subconfluence on a glass coverslip and incubated for 24–48 h in the presence or absence of 50 µM mitotane, briefly rinsed with warm PBS, and then fixed in 3% paraformaldehyde in PBS. Mitochondria were labeled with antibodies against COX2 subunit as described (Agier et al. 2012).

Statistical analysis

Results are expressed as means±s.e.m. of n independent replicates performed in the same experiment or from n separated experiments. Differences between groups were
analyzed using nonparametric Kruskal–Wallis ANOVA followed by Dunn’s multiple comparison test or nonparametric Mann–Whitney U test as appropriate. The significance level was $P<0.05$.

**Results**

**Mitotane treatment reduces human adrenocortical H295R and SW13 cell proliferation**

Proliferation index was calculated using the colorimetric solution Celltiter 96. Exposure to mitotane for 48 h inhibited the proliferation of H295R and SW13 cells in a dose-dependent manner, 100 $\mu$M $o,p'$-DDD significantly reducing the proliferation rate of H295R by 45% and that of SW13 cells by 30% (Fig. 1A and B). The anti-proliferative effect of mitotane was also time dependent, 100 $\mu$M mitotane inhibiting the proliferation of H295R cells by 18% after 24 h and by 70% after 72 h. Subsequent experiments were performed using 50 $\mu$M mitotane to minimize the drug’s potential cytotoxic effects.

**Effect of mitotane on steroidogenesis in H295R cells**

To confirm the ability of mitotane to inhibit hormone secretion, we measured several steroid hormone concentrations in the culture supernatant of H295R cells. Exposure to 50 $\mu$M mitotane for 48 h significantly reduced the secretion of both cortisol and 17-OH-progesterone about 80% by H295R cells (Fig. 1C). Other steroid hormones such as aldosterone were undetectable in culture supernatants under these experimental conditions.

To address the mechanisms underlying this decreased steroid secretion, we analyzed the expression of genes that encode mt effectors of steroidogenesis by qRT-PCR. Mitotane significantly decreased the expression of such genes: $STAR$, which encodes the STAR that transports cholesterol into mitochondria, the first rate-limiting step for the intra-mt steroidogenic pathway (80% inhibition after 48 h; Fig. 2A); cholesterol desmolase ($CYP11A$ ($CYP11A1$)), 3β-hydroxysteroid dehydrogenase ($HSD3B2$); 11β-hydroxylase ($CYP11B1$), which catalyzes 11-deoxycorticosterone and 11-deoxycortisol transformation into corticosterone and cortisol respectively (75% inhibition; Fig. 2B); and aldosterone synthase ($CYP11B2$), the last intra-mt enzymatic step in aldosterone synthesis (97%, inhibition; Fig. 2C). The mitotane-induced inhibition of steroid secretion observed in H295R cells therefore appeared to be due to decreased expression of the steroidogenic enzymes.
Effect of mitotane on the respiratory chain

The impact of mitotane on respiratory chain activity was evaluated by spectrophotometric assays of the activities of the four mt respiratory complexes in H295R and SW13 cells treated with vehicle (DMSO) or 50 \( \mu \)M mitotane during 48 h (Table 1). Citrate synthase activity, belonging to the mt citric acid cycle, was used as an index of the mt mass. Its activity was very high in H295R cells (299 ± 22 nmol/min per mg protein; \( n = 12 \)) but lower in SW13 cells (159 ± 11 nmol/min per mg protein; \( n = 8 \)), suggesting that H295R cells have a greater mt population than SW13 cells consistent with their important steroidogenic capacity. However, citrate synthase activity was not affected by mitotane exposure (260 ± 31 nmol/min per mg protein in H295R and 135 ± 7 nmol/min per mg protein in SW13 cells).

Both H295R and SW13 mitotane-treated cells exhibited a significant COX (or complex IV) defect of ~ 50% after 48 h while complex II (succinate–ubiquinone oxidoreductase) appeared unaffected (Table 1). Complex III (ubiquinol–cytochrome c oxidoreductase) activity remained unchanged in H295R cells and was slightly reduced in SW13 cells after mitotane treatment (Table 1), but this decrease was not confirmed after normalization to citrate synthase activity (Table 1). Complex I (NADH–ubiquinone oxidoreductase) activity can only be reliably

Table 1  Mitochondrial respiratory activities.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>H295R cells</th>
<th>SW13 cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>Citrate synthase</td>
<td>299 ± 22</td>
<td>260 ± 31</td>
</tr>
<tr>
<td>Vehicle</td>
<td>159 ± 11</td>
<td>135 ± 7</td>
</tr>
<tr>
<td>50 ( \mu )M mitotane</td>
<td>260 ± 31</td>
<td>283 ± 53</td>
</tr>
<tr>
<td>Complex I</td>
<td>8.3 ± 0.7</td>
<td>43 ± 9</td>
</tr>
<tr>
<td>Vehicle</td>
<td>37 ± 3</td>
<td>32 ± 1</td>
</tr>
<tr>
<td>50 ( \mu )M mitotane</td>
<td>43 ± 9</td>
<td>127 ± 37†</td>
</tr>
<tr>
<td>Complex II</td>
<td>55 ± 8</td>
<td>48 ± 6</td>
</tr>
<tr>
<td>Vehicle</td>
<td>55 ± 10*</td>
<td>55 ± 10*</td>
</tr>
<tr>
<td>50 ( \mu )M mitotane</td>
<td>55 ± 10*</td>
<td>55 ± 10*</td>
</tr>
<tr>
<td>Complex III</td>
<td>95 ± 14</td>
<td>86 ± 26</td>
</tr>
<tr>
<td>Vehicle</td>
<td>89 ± 6</td>
<td>89 ± 6</td>
</tr>
<tr>
<td>50 ( \mu )M mitotane</td>
<td>89 ± 6</td>
<td>127 ± 37†</td>
</tr>
<tr>
<td>Complex IV</td>
<td>276 ± 15</td>
<td>153 ± 19†</td>
</tr>
<tr>
<td>Vehicle</td>
<td>283 ± 53</td>
<td>283 ± 53</td>
</tr>
<tr>
<td>50 ( \mu )M mitotane</td>
<td>153 ± 19†</td>
<td>153 ± 19†</td>
</tr>
<tr>
<td>CI/CS</td>
<td>0.28 ± 0.03</td>
<td>0.21 ± 0.03</td>
</tr>
<tr>
<td>Vehicle</td>
<td>0.26 ± 0.02</td>
<td>0.30 ± 0.04</td>
</tr>
<tr>
<td>50 ( \mu )M mitotane</td>
<td>0.26 ± 0.02</td>
<td>0.30 ± 0.04</td>
</tr>
<tr>
<td>CII/CS</td>
<td>0.29 ± 0.03</td>
<td>0.36 ± 0.07</td>
</tr>
<tr>
<td>Vehicle</td>
<td>0.68 ± 0.07</td>
<td>0.68 ± 0.10</td>
</tr>
<tr>
<td>50 ( \mu )M mitotane</td>
<td>0.78 ± 0.08</td>
<td>0.56 ± 0.01*</td>
</tr>
<tr>
<td>CIV/CS</td>
<td>1.05 ± 0.08</td>
<td>0.52 ± 0.02†</td>
</tr>
</tbody>
</table>

Enzymatic activities were measured in cell homogenates with the exception of complex I, which was measured on purified mitochondrial fractions; values are mean ± S.E.M. of 6–12 independent experiments, expressed as nmol/min per mg protein. Ratio between complex II or complex III or complex IV/citrate synthase (CS) activities is also presented. **P < 0.01 and ***P < 0.001 with nonparametric Mann–Whitney U test.
measured on purified mt fractions due to the presence of numerous non-mt NADH oxidase activities in cell homogenates but its activity was greatly decreased after exposure to mitotane in both human adrenocortical cell lines after exposure to mitotane (Table 1). Altogether, our results demonstrate that mitotane selectively inhibits some but not all respiratory chain complexes.

The effect of mitotane on complex IV was concentration dependent, as shown in Fig. 3, with an IC_{50} calculated at ~67 µM mitotane (linear regression test; \( y = 92.862 - 0.583x, r^2 = 0.97 \)). This mitotane concentration corresponds to the therapeutic plasma threshold predictive of efficacy in clinical practice (Haak et al. 1994, Baudin et al. 2001).

To examine whether o,p'-DDD might directly affect the enzymatic activity of complex IV, we measured COX activity on cell homogenates incubated with increasing concentrations of mitotane. Under these conditions, we demonstrated that mitotane dose dependently decreased complex IV activity with an IC_{50} of ~133 µM (linear regression test; \( y = 100.2 - 0.3749x, r^2 = 0.96 \); Fig. 4). This IC_{50} in the cell homogenate system is twice as high as the IC_{50} observed when whole cells were treated for 48 h, indicating that mitotane exerts both direct and indirect inhibitory effects on COX activity. Our results strongly suggested that mitotane inhibits enzymatic activity directly but presumably inhibits the expression of the enzyme. We therefore studied the expression of COX at both the mRNA and protein levels. The COX complex consists of 13 subunits, three of which, including COX2, are encoded by the mt genome while the remaining ten subunits, including COX4 (COX4I1), are encoded by nuclear genes. We observed that the steady-state levels of mt and nuclear DNA-encoded COX2 and COX4 transcripts in both H295R and SW13 cells were drastically decreased (by 70%) in H295R cells after exposure to 50 µM mitotane for 48 h (Fig. 5A and B). Similar results were obtained in SW13 cells (data not shown).

We analyzed the whole respiratory chain complexes by blue native PAGE (BN-PAGE). Immunoblotting with antibodies directed against a component of each mt complexes revealed that mitotane exposure for 48 h induced a 45–70% decrease in the steady-state expression of complex IV and complex I proteins while the abundance of complexes II and III appeared unchanged (Fig. 5C and D). These data were fully consistent with the decreased enzymatic activities described earlier (Table 1). Altogether, our results demonstrate that mitotane has deleterious consequences by acting at the mRNA and protein level to impair respiratory chain expression and function.
mitotane for 48 h. However, this ratio increased significantly after treatment with 100 μM mitotane and with longer exposure times (e.g., 50 μM mitotane for 72 h), suggesting the presence of a compensatory response of mt biogenesis (Fig. 6B). To further explore this hypothesis, we quantified the expression of peroxisome proliferator-activated receptor gamma coactivator 1α (PGC1α (PPARGC1A)), a transcriptional coactivator considered a key regulator of mt biogenesis. PGC1α mRNA expression was slightly but significantly induced.

Figure 5
Inhibition of the expression of the respiratory chain genes and proteins by mitotane. The steady-state levels of mRNA encoding for the mitochondrial DNA-encoded COX2 (A) and the nuclear DNA-encoded COX4 (B) were measured by RT-qPCR. The expression of both COX2 and COX4 transcripts was drastically reduced after exposure to 50 μM mitotane for 48 h. Results are expressed as the mean percentage ± S.E.M. of four independent determinations performed in duplicate of the expression measured in untreated cells, arbitrarily set at 100%. *P < 0.05 and ***P < 0.001, Mann–Whitney U test. Steady-state levels of respiratory chain whole complexes were analyzed by BN-PAGE followed by western blot with anti-GRIM 19 (a subunit of complex I), anti-70 kDa (a subunit of complex II), anti-core2 (a subunit of complex III), and anti-COX1 (a subunit of complex IV) (C). Band intensities were quantified by ImageJ Software revealing that mitotane reduced the steady state of both the complex I and the complex IV and were reduced by 45–70% but had no effect on complex II or complex III expression (D). Results are expressed as the mean percentage ± S.E.M. of four independent determinations of the expression measured in untreated cells, arbitrarily set at 100%. *P < 0.05, Mann–Whitney U test.
by 50 μM mitotane treatment for 48 h, suggesting activation of transcriptional response (Fig. 6C). Furthermore, no mtDNA mutations or deletions were found by sequencing mtDNA from mitotane-treated cells.

**Effect of mitotane on mt morphology**

Finally, to get an integrated evaluation of the mitotane-induced mt respiratory chain defect, we analyzed the mt morphology by immunocytochemistry using an antibody against COX2. Treatment with 50 μM mitotane induced drastic morphological alterations in the mitochondria of adrenocortical cells. In the absence of treatment, the mt compartment appeared as a highly interconnected tubular network with a filamentous appearance. However, after exposure to the drug the compartment exhibited a more punctiform pattern, consistent with mt fragmentation (Fig. 7).

**Discussion**

Even though combination of mitotane and cisplatin-based chemotherapy has been recently shown to clinically improve the overall survival in advanced ACC (Fassnacht et al. 2012), mitotane remains the single most active pharmacological option for the management of ACC, as recognized in recent recommendations (Berruti 2012). However, its mechanism of action still remains unclear. In this study, we addressed the question on the mt effects of mitotane on two different human adrenocortical cell lines derived for human ACC aiming at identifying potential molecular targets of the drug. Attempts to perform similar experiments on primary human ACC cells have been so far unsuccessful.

We found that at optimal therapeutic concentrations (50 μM, i.e. 14–20 mg/l), mitotane drastically altered mt function in both steroid-secreting and non-secreting adrenocortical cell lines derived for human ACC. Mitotane inhibited steroid hormone production and secretion, which was accompanied by a reduction in steady-state mRNA levels of genes encoding mt proteins involved in steroidogenesis pathways. More importantly, we demonstrated for the first time that exposure to 50 μM mitotane significantly impairs the mt respiratory chain. Mitotane exposure also stimulated mt biogenesis and altered mt morphology in adrenocortical cells.

It is well established that the in vivo anti-proliferative efficacy of mitotane depends on its circulating plasma level (Baudin et al. 2001). However, its pharmacokinetic profile with an unmet need for improved bioavailability...
and its metabolic conversion constitute potential limitations (Schteingart 2007). It has been suggested that the metabolic transformation of mitotane by CYP3A4 (van Erp et al. 2011, Kroiss et al. 2011), which is likely responsible for the pharmacokinetic interaction whereby mitotane reduces plasma levels of sunitinib (Fassnacht et al. 2012, Kroiss et al. 2012), has been suggested that CYPc11 or CYP11B1 could be involved in tissue-specific and compartment-selective mitotane metabolism (Lund & Lund 1995, Lindhe et al. 2002). Although CYP11B1 may catalyze the initial hydroxylation step of mitotane (Cai et al. 1995, Lund & Lund 1995, Lindhe et al. 2002), its direct involvement in mt dysfunction is very unlikely given that SW13 cells, which do no express CYP11B1, were similarly affected by mitotane treatment. In any case, the relationship between the potential hepatic metabolism of mitotane and its adrenal effect remains currently unknown. For instance, it remains to be established whether intra-mt transformation of mitotane into 0,p'-DDA and 0,p'-DDE compounds has deleterious consequences on OXPHOS. However, preliminary results from our laboratory reveal the presence of active mitotane uptake into H295R cells, suggesting that intracellular accumulation of mitotane and/or one of its metabolites may account for its cytotoxic effects.

Given that most enzymatic steps of steroid hormone biosynthesis take place in the mitochondria and that mitotane inhibits steroidogenesis, we examined whether mitotane impedes mt respiratory chain function. Interestingly, in both H295R and SW13 cells, OXPHOS analyses indicated that mitotane induced a significant and selective decrease in the maximum velocity of COX activity, whereas complex II and III activities were unaltered. Mitotane has both direct and indirect inhibitory effects on COX: direct inhibition of the enzymatic activity was revealed in our experiments on cell homogenate incubation with 0,p'-DDD but the drug also inhibited expression of the enzyme at both the mRNA and protein levels. Inhibition of gene expression was observed for both the mtDNA-encoded COX2 and the nuclear DNA-encoded COX4 subunits. Immunoblotting provided additional support for a reduction in steady-state COX protein expression. Concomitantly, normal activity and expression of respiratory chain complexes II and III or of citrate synthase, a Krebs cycle enzyme, suggest that mitotane caused selective enzymatic disruption rather than global mt damage, as initially proposed (Kaminsky et al. 1962).

The mitotane transformation into active acylchlorine metabolites that takes place in the mitochondria of adrenal gland is believed to be responsible for cell toxicity and may explain the selective adrenolytic effect of the drug (Cai et al. 1995, Lindhe et al. 2002). This hypothesis awaits further confirmation at the clinical level (Hermsen et al. 2011). At variance with the hepatic microsomal transformation of mitotane by CYP3A4 (van Erp et al. 2011, Kroiss et al. 2011), which is likely responsible for the pharmacokinetic interaction whereby mitotane reduces plasma levels of sunitinib (Fassnacht et al. 2012, Kroiss et al. 2012), it has been suggested that CYPc11 or CYP11B1 could be involved in tissue-specific and compartment-selective mitotane metabolism (Lund & Lund 1995, Lindhe et al. 2002). Although CYP11B1 may catalyze the initial hydroxylation step of mitotane (Cai et al. 1995, Lund & Lund 1995, Lindhe et al. 2002), its direct involvement in mt dysfunction is very unlikely given that SW13 cells, which do no express CYP11B1, were similarly affected by mitotane treatment. In any case, the relationship between the potential hepatic metabolism of mitotane and its adrenal effect remains currently unknown. For instance, it remains to be established whether intra-mt transformation of mitotane into 0,p'-DDA and 0,p'-DDE compounds has deleterious consequences on OXPHOS. However, preliminary results from our laboratory reveal the presence of active mitotane uptake into H295R cells, suggesting that intracellular accumulation of mitotane and/or one of its metabolites may account for its cytotoxic effects.

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Herein, we confirm the adrenolytic effect of mitotane by showing that mitotane exposure leads to a time- and concentration-dependent reduction of adrenocortical cell numbers. Interestingly, this was accompanied by enhanced mt biogenesis, as demonstrated by increased mtDNA content and PGC1α expression, reminiscent of a cellular compensation mechanism in response to the respiratory chain defect. This adaptive pathway, combining increased mt mass, increased mtDNA copy level and impaired OXPHOS, which has already been reported in mt myopathies caused by mtDNA mutations (Srivastava et al. 2009). However, no mtDNA mutations or deletions were found by sequencing mtDNA from mitotane-treated cells. Of particular interest, mtDNA exposure also triggered morphologic fragmentation of the mt network, which could be related to disequilibrium between mt fission and fusion (Chen & Chan 2010). It is well established that the integrity of mt outer and inner membranes is required for respiratory chain activity (Liesa et al. 2009, Chen et al. 2010) and presumably steroidogenesis (Duarte et al. 2012). It is not known, however, whether mt fragmentation has a direct relationship with or a causal role in genotoxic stress and apoptosis.

In summary, our results show that mitotane alters mt respiratory chain activity in human adrenocortical cells, notably by inducing a COX defect. Further studies are needed to examine whether and how such mitotane-induced mt dysfunction translates into adrenolytic and antitumor effects on human ACC (Costa et al. 2011).

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