Expression of Deoxynucleotide Carrier is not associated with the mitochondrial DNA depletion caused by anti-HIV dideoxynucleoside analogs and mitochondrial dNTP uptake

Wing Lam, ChinShing Chen, Shuolun Ruan, Chung-Hang Leung and Yung-Chi Cheng.

Department of Pharmacology, Yale University, New Haven, CT 06520
a. Running Title: Expression of Deoxynucleotide Carrier

b. Address correspondence to: Dr. Yung-chi Cheng, Department of Pharmacology, Yale University School of Medicine, New Haven, CT 06520. Tel.: 203-785-7120; Fax: 203-785-7129; E-mail: cheng.lab@yale.edu.

c. The number of text pages, 19

   The number of tables, 1

   The number of figures, 9

   The number of references, 18

   The number of words in abstract, 240

   The number of words in introduction, 459

   The number of words in discussion, 1049

d. Abbreviations: mtDNA, mitochondrial deoxyribonucleic acid; DNC, deoxynucleotide carrier; ddC, β-D-2',3'-dideoxycytidine; d4T, 2',3'-didehydro-2',3'-dideoxythymidine; ddI, 2',3'-dideoxyinosine; ROS, reactive oxygen species.
Abstract

Our previous studies suggested that the dNTP/dNDP transporter systems, that exist in mitochondria for transporting dNTP/dNDP from the cytoplasm to the mitochondria for mitochondrial DNA (mtDNA) synthesis, play a critical role in delayed cytotoxicity of anti-HIV dideoxynucleoside analogs in mitochondria. Recently, a protein, termed mitochondrial deoxynucleotide carrier (DNC), based on its ability to transport dNTPs in reconstituted proteoliposomes was isolated. Lacking cellular information to substantiate DNC’s involvement in the delayed cytotoxicity of dideoxynucleoside analogs, we expressed DNC and reconstituted it into proteoliposomes. The Km values for dNTPs uptake by reconstituted DNC were in the mM range which is a thousand fold higher than that of the physiological level. Further, we found that over-expressing DNC (wt and G177A-mutated DNC) in RKO cells did not sensitize the cells to the mtDNA depletion caused by ddC, d4T and ddI or affect the mtDNA recovery rate after ddC treatment. Mitochondria isolated from DNC over-expressing cells did not significantly differ from that isolated from RKO cells in terms of the rate of uptake or the incorporation of dTTP into mitochondria DNA. Down-regulation of DNC expression by siRNA was also ineffective in changing the action of dideoxynucleoside analogs on the mtDNA depletion, and the rate of dTTP uptake into isolated mitochondria. Down-regulation of both DNC and TK2 also did not cause mtDNA depletion. We conclude that DNC does not play an important role in the delayed cytotoxicity (mtDNA depletion) of anti-HIV dideoxynucleoside analogs and dNTPs uptake into mitochondria.
Introduction

At clinical dosage, anti-HIV dideoxynucleoside analogs such as AZT, d4T, ddC and ddI could cause delayed type toxicity such as myopathy, cardiomyopathy, peripheral neuropathy, lipodystrophy and lactic acidosis in patients [White, 2001]. Based on cell culture studies we postulated that the delayed toxicity could be due to the action of those compounds in depleting cellular mtDNA through their incorporation at the terminal of mtDNA [Chen and Cheng, 1989; Chen, et al., 1991].

In order to have dNTPs for mtDNA synthesis, dNTPs must be either imported from the cytoplasm through a carrier or synthesized by salvaging deoxynucleosides within the mitochondria [Elpeleg et al., 2002]. The existence of a mechanism for mitochondria dNTP uptake was suggested by DNA synthesis experiments using isolated mitochondria employing dNTPs which could be utilized for synthesizing mtDNA [Parsons and Simpson, 1973; Enriquez, et al., 1994; Chen and Cheng, 1992].

For ddC to deplete mtDNA, since ddC cannot be phosphorylated to ddCTP in mitochondria, it will require the transport of ddCTP from the cytoplasm to the mitochondria, [Chen and Cheng, 1992]. ddC is unable to deplete mtDNA in cytoplasmic dCyd kinase-deficient CEM cells [Chen and Cheng, 1992]. The presence of a mitochondria associated dNTP transport system was further demonstrated by using a proteoliposome system reconstituted with partially purified mitochondrial proteins [Bridges, et al., 1999]. The dCTP transport activity in proteoliposomes was time-dependent and could be activated by Ca\(^{2+}\). The Km value of dCTP in the presence of Ca\(^{2+}\) was shown to be 3 \(\mu\)M, within physiological range. dCDP but not dCMP or dCyd could
inhibit the transport activity. Other deoxynucleoside triphosphates could also inhibit the uptake of dCTP with a potency the order of dGTP = dATP > TTP.

Recently, protein from the gene, SLC25A19, has been termed a deoxynucleotide carrier (DNC, 36 kD) and it was suggested to be a mitochondria transporter located on the inner membrane [Dolce, et al., 2001]. Functional analysis showed that DNC in a reconstituted proteoliposome system could transport dNTPs. It was postulated to be associated with the delayed cytotoxicity of dideoxynucleoside analogs. Correlations with a of mutation of this protein (gly177-to-ala (G177A)) and Amish lethal microcephaly was found [Rosenberg, et al., 2002]. Functional analysis indicated that the G177A-mutated DNC protein in proteoliposome could not uptake dATP. They proposed that mitochondrial deoxynucleotide transport may be essential for the prenatal brain growth.

Cellular information to support whether DNC is a key transporter of dNTP uptake into mitochondria and associated with mtDNA depletion caused by dideoxynucleoside analogs is not available. In this paper, we studied the behavior of DNC in vitro. Our results suggest that the DNC is not associated with the delayed cytotoxicity caused by dideoxynucleoside analogs and not important in dNTPs uptake into mitochondria. The term “deoxynucleotide carrier; DNC” should be reconsidered.
**Materials and Methods**

**Expression of DNC**

Human DNC with C-terminal His-tag expression was constructed as previously reported [Dolce, et al., 2001]. DNC protein was expressed in *E. coli* BL21(DE3) and was purified as previous described [Dolce, et al., 2001]. The dNTP transport activities of DNC were also assayed as previously described [Dolce, et al., 2001].

**Reconstitution of DNC**

Liposomes were prepared by the size extrusion [MacDonald, et al., 1991]. Desired amounts of cholesterol or cardiolipin were added to egg yolk or soy bean phosphatidylcholine (Avanti Polar Lipid, Alabaster, AL) in chloroform. Mixtures were dried in vacuum overnight. The dried lipid was dissolved in buffer (Pipes 20mM pH 6.3, EDTA 1mM) to a final concentration of 10% (w/v) by intensely vortexing. The mixture was frozen (liquid nitrogen) and thawed (37°C water bath) three times and passed through a 100 nm polycarbonate membrane filter 13 times. Proteoliposomes were generated by the detergent removal method [Palmieri, et al., 1995]. 826 µl of 20 mM pipes at pH 6.3, 1 mM EDTA, was mixed with 180 µl of 10% Triton X-114, 16 µg of DNC, and 220 µl of 10% liposome. After vortexing, the detergent was removed by passing through the same column packed with 2 ml of ambersite XAD 1X200 13 times. The amount of DNC protein incorporated into liposomes varied between 15% and 25% of the protein added to the reconstitution mixture. [α-32P] dATP, dCTP and dTTP 4mM-200µM (100 Ci/mmol) were used to study uptake activity of DNC at 37°C. Dowex ion
exhange columns (Sigma Chemical Co., St. Louis, MO) (1x3.5cm) were used to remove
the external radioactivity not transported into proteoliposomes [Bridges, et al., 1999].

**Cell Culture, Transfection, and Cloning of Stable Transfectants.**

DNC was cloned into the RVYtet vector, a tet-off system (kindly provided by Dr. David
Ward). Site-directed mutagenesis (QuikChangeXL; Stratagene, La Jolla, CA) was used to
change the nucleotide at 530 from G into C (amino acid at 177 from G to A). Retrovirus
were generated by co-transfection of RVYtet-DNC and PVSVG into GP2-293 cells using
the standard calcium phosphate method. After 48h, medium containing retrovirus was
used to transfect RKO cells. The transfectants were selected by growing cells in culture
medium containing hydromycin B 250µg/ml and doxycycline 1µg/ml. Expression of
DNC was induced by removing doxycycline from culture medium. Immunofluorescent
microscopy was used to check the clones expressing DNC. Clones with homologous
expression of DNC were isolated and expanded.

**siRNA Transfection**

2 x 10^5 RKO cells grown in RPMI 1640 supplemented with 10% fetal bovine serum
(FBS), were plated into 6-well plates, 4h before transfection (Day-0). Cationic lipid
complexes were prepared by incubating 200 nmol/ml siRNA (DNC Sense sequence
=5′CCUCCAAAACCUGCUUUUGUtt3′, Control Sequence =5’
GUUCCUCAACUUCUAGCAUUt3′, synthesized from Dharmacon (Dharmacon
Lafayette, Colorado) with 6 µl of Oligofectamine (Invitrogen, Carlsbad, California) in
200 µl of OPTI-MEM (Invitrogen, Carlsbad, California) for 15 min. The complexes were
added to the cells to a final volume of 0.8 ml. After incubation for 4 h, 0.5 ml of RPMI
supplemented with 30% FBS was added to each well. The transfection was repeated the next day (Day-1). On Day 2, cells from each well were reseeded in the absence of siRNA, based on the experimental requirements. The TK2 (thymidine kinase-2) siRNA was purchased from Ambion (Ambion, Austin, TX).

**Generation of Monoclonal Antibody and Western blotting**

The purified recombinant DNC protein (50 µg), mixed with Freund’s complete adjuvant (Sigma Chemical Co., St. Louis, MO), was used as the antigen to immunize 4 week balb/c mouse. The mouse was immunized twice more at 2 week interval with a mixture of DNC protein and Freund’s incomplete adjuvant. The mouse was then boosted by injection of DNC protein (25 µg) intravenously. After 4 days, the mouse was terminated and the spleen cells were fused with Sp2/0-Ag14 cells using PEG1000. HAT was used to select hybridoma cells. Cloning was performed using the limiting dilution. Standard indirect ELISA was used to screen for the hybridoma clones producing antibody against DNC. Monoclonal antibody production was demonstrated by Western blotting with total lysate of *E. coli* containing recombinant human DNC protein. SDS-PAGE was performed as described by Laemmli [Laemmli, 1970]. The protein was then transferred to nitrocellulose membranes (Bio-Rad Laboratories, Hercules, CA) with a Miniprotein II transferring apparatus (Bio-Rad). The membranes were blocked and probed in PBS-T buffer (1x PBS buffer, 0.2% Tween 20) containing 5% non-fat milk. The immunoreactive bands were visualized by enhanced chemiluminescence reagents (Perkin-Elmer Life Science Products, Boston, MA), and densitometry scanning was performed with the personal densitometer (Molecular Dynamics).
Mol Manuscript #7120

Confocal Microscopy

Briefly, $10^5$ cells were seeded onto 22 mm x 22 mm glass coverslips in 35-mm culture dishes and incubated overnight. Cells were fixed with 4% paraformaldehyde in PBS and then permeabilized by 0.5% Triton X-100 in PBS. To block nonspecific binding, 1% BSA in PBS was used. DNC protein was targeted by DNC monoclonal antibody (C5-1-2) at 1:100 dilution followed by FITC-conjugated anti-mouse IgG at 1:100 dilution. Mitochondria were counterstained with 500 nM Mito-tracker (Molecular Probes, Eugene, OR). Cells were sealed in anti-fade reagent (Molecular Probes). Confocal micrographs were scanned by a laser scan confocal microscope, LSM 510 (Zeiss).

Determination of mtDNA Content.

Aliquots of cells cultured in the presence or absence of drugs were harvested by centrifugation (800xg) and were washed twice with PBS. Cell pellets were resuspended in 100 µl of 10 mM Tris-HCl (pH 7.5) and were subjected to three freeze-thaw cycles. The cell lysates were incubated with RNaseA (10 µg/ml) at 37 °C for 1h. The samples were then treated with proteinase K (100 µg/ml) at 55 °C for 3h. After incubation, an equal volume of 20X standard saline citrate (SSC; 1xSSC is 0.15 M NaCl plus 0.015 M sodium citrate) was added to each sample. The lysates were spotted onto Hybond paper by using Miliford II slot blot apparatus (Schleicher & Schuell). mtDNA quantification was based on total cell number and was detected with an mtDNA-specific probe. Cellular DNA, as an internal control, was probed by an Alu DNA probe, as described previously [Chen, et al., 1991]. The intensities of the autoradiographic bands were quantified by a scanning densitometer.
Cell Growth Assay

Exponentially growing cells were plated in a 24-well plate (1 x 10^4 cells/well). After desired time, cells were fixed and stained for 2 h with 0.5% methylene blue in 50% ethanol, followed by washing with tap water to remove unbound dye. Plates were air dried and then cells were dissolved in 1% sarkosyl by shaking at room temperature for 3 h. Cell growth was quantitated based on the amount of methylene blue adsorbed by the cells as measured by a spectrophotometer (Molecular Devices) at 595 nm. All experiments were performed in triplicate wells and were repeated at least three times.

Lactic Acid Determination

Lactic acid production in cell culture medium on Day 4 was determined by using a lactic acid determination kit based on colorimetric development in an enzymatic reaction: lactic acid and NAD are converted to pyruvic acid and NADH (absorbance, at 360nm) by lactate dehydrogenase (Sigma-Aldrich, St Louis, MO).

Mitochondria Potential Determination

After being seeded on cover-slip for 1 day, cells were incubated with 1µM JC-1 in serum free medium for 30min at 37 °C (in live cells, JC-1 exists either as a green-fluorescent monomer at depolarized membrane potentials or as an orange-fluorescent J-aggregate at hyperpolarized membrane potentials). After washing with PBS, the living cells were illuminated at 488nm and the emission was collected at 515nm (green) and 580nm (red) by using flow-cytometry (Dackon).

Reactive Oxygen Species
The level of reactive oxygen species in cells was measured using 5-(and-6)-
chloromethyl-2’,7’-dichlorodihydrofluorescein diacetate, acetyl ester (CM-H₂DCFDA)
(Molecular Probes, Eugene, OR). Briefly, cells seeded overnight were incubated with
1µM of CM-H₂DCFDA for 30 min at 37⁰C. Pancreatin was used to form single cell
suspensions which were subjected to flow-cytometry. Cells were illuminated at 488nm
and the emission was collected at 515nm.

Mitochondria Calcium

The level of mitochondria calcium was determined using rhod-FF-AM (a lower-affinity
Ca²⁺ indicator that accumulates primarily in mitochondria). Briefly, cells seeded
overnight were incubated with 1µM of rhod-FF-AM for 30min at 37⁰C. Pancreatin was
used to form single cell suspensions which were subjected to flow-cytometry. Cells were
illuminated at 540nm and the emission was collected at 580nm.

dNTP Uptake and DNA synthesis in Isolated Mitochondria

Mitochondria of RKO cell lines were isolated by the “two-step” procedure described by
Bogenhagen and Clayton [Bogenhagen and Clayton, 1974]. The reactions were
performed using the methods described by Chen and Cheng [Chen and Cheng, 1992]. 3
µM dATP, dCTP, dGTP and 1 µM [α-³²P]dTTPs (50 Ci/mmol; Amersham Biosciences)
were used in the assay. Mitochondria (100 µg of protein per reaction for DNA synthesis,
25 µg of protein per reaction for dNTP uptake assay) in a total volume of 0.2 ml was used
for each assay. The reactions were carried out at 37⁰C, for 2 min for the uptake assay and
2 hr for the DNA synthesis assay. For the DNA synthesis assay, ice cold 15%
Trichloracetic acid was used to precipitate acid-insoluble fractions from the reaction. The
acid-insoluble pellets were washed 3 times with 10% trichloracetic acid. The pellets were dissolved in 200 µl of 0.5% sarkosyl in 0.1 M sodium phosphate buffer at pH 7.4.
Results

Dependence of dCTP uptake on cardiolipin and cholesterol content in proteoliposomes

It was reported that cardiolipin could promote DNC activity [Dolce, et al., 2001]. We compared whether cardiolipin could promote dCTP uptake activity of DNC in the liposome prepared with phosphatidylcholine purified from either egg yolk or soybean.

Without cardiolipin both phosphatidylcholine sources resulted in similar dCTP uptake activity. However, cardiolipin (plateau at 15%) could stimulate dCTP uptake selectively from the liposome prepared from phosphatidylcholine purified from egg yolk but not soybean (Fig. 1).

Many reports had suggested that cholesterol could promote the activity of membrane transporters. We tested whether this phenomenon was applicable to DNC. We found that dCTP uptake activity of DNC could be promoted by cholesterol in either type of phosphatidylcholine. The combined effect of cardiolipin and cholesterol was also studied. Cholesterol could enhance the stimulating activity of cardiolipin at 15% but not at lower concentrations when egg yolk phosphatidylcholine was used (Fig. 1).

Effect of metal divalent ions on dCTP uptake activity of DNC

Since our previously described dCTP transporter required calcium to function optimally [Bridges, et al., 1999], we tested the effect of different divalent metal ions on the dCTP uptake activity of DNC.

We found that none of the divalent metal ions could stimulate the DNC activity. In fact, 2mM calcium chloride inhibited 70% of the activity of DNC (Fig. 2).

Kinetic properties of DNC
Km and Vmax values of DNC were determined by using an optimized cardiolipin (15%) concentration with or without 10% cholesterol. DNC had higher Km and Vmax values for dCTP than those for dATP and dTTP. Internal ADP had little effect on the Km values but decreased the Vmax values (Table 1).

The addition of cholesterol increased the Vmax values by 3-fold for dCTP, 5-fold for dATP and 1.5-fold for dTTP (Table 1). Cholesterol increased Km values for dATP but had less impact on that of dCTP and dTTP. When considering relative efficiency (Vmax/Km), addition of cholesterol had more impact on dCTP than dATP and dTTP.

**Presence and localization of DNC protein in cells**

The intrinsic levels of DNC protein in RKO cells could not be detected by our monoclonal antibody. Stable cell lines established by infection with RVVtet-DNC’s retrovirus and hydromycin B selection show low levels of DNC protein expression when growing in medium containing 3 µg/ml doxycycline (without affecting the growth of cells). This may be due to leakage of the tet-off system. DNC protein was highly expressed 72h after removing doxycycline from the medium (Fig. 3A). The size of DNC protein (36kDa) expressed from DNC cells or DNC-G177A cells was the same as the DNC expressed from *E.coli*. This indicated that integral DNC protein was imported into the mitochondria (also see confocal pictures) with no apparent post-modification of DNC.

When DNC protein was induced in DNC cells or DNC-G177A cells, bright green fluorescence from anti-mouse-FITC which recognizes the DNC monoclonal antibody, can be overlapped with the red fluorescence from mito-tracker which stains specifically mitochondria (Fig. 3B). Moreover, the green fluorescence from the mitochondria could be blocked by pre-mixing purified DNC protein with the mAb-DNC (data not shown).
Mutation of G177A did not affect the localization of DNC in mitochondria. Furthermore, the density and shape of the mitochondria of cells expressing mutated G117A DNC did not change significantly as compared to that of the cells expressing wild type DNC.

**Effect of DNC protein expression on cell growth and mitochondria functions**

DNC protein or mutated G177A DNC expression did not affect the rate of RKO cell growth. We studied several cellular parameters that may be influenced by the functional status of mitochondria, including lactic production, mitochondria potential, cellular ATP/ADP level, ROS level, GSH level and mitochondria calcium. All of the above parameters were not affected significantly by the expression of wild type or G177A mutated DNC (results not shown).

**Effect of over-expression of DNC on the mtDNA depletion and the lactic acid production caused by dideoxynucleoside analogs (ddC, d4T, ddI)**

The ability to cause the mtDNA depletion and induced lactic acid production in RKO cells was ddC>ddI>d4T.

Results indicate that the mtDNA depletion and induced lactic production caused by ddC and ddI were not affected by the over-expression of wt DNC and G177A mutated DNC (Two-way ANOVA, P>0.05) (Fig. 4).

A high concentration of d4T (100 µM) caused less mtDNA depletion in induced RKO cells which contained a higher level of DNC (P<0.05) than for control or G177A-mutated DNC (Fig. 4A). However, induced lactic acid production was similar at 100 µM of d4T (Fig. 4B). After longer treatment (6 days instead of 4 days) the cells with lower dosage (6 and 25 µM) of d4T did not increase the difference of the inhibitory effect of
mtDNA between DNC induced and non-induced cells (results not shown). Results from the high dose (100 µM) of d4T and longer treatment (6 days) were not considered because the cell growth inhibition was more than 40% as compared to less than 10% cell growth inhibition with the low dose of d4T (result not shown).

Effect of over-expressing DNC on the ability of mtDNA to recover from ddC treatment

Cell lines with or without over-expressing DNC were treated by ddC at 20 µM for 4 days. mtDNA was measured at different times after re-seeding the cells. Results showed that ddC had similar potency in cell lines causing mtDNA depletion down to about 10% of control mtDNA. After removal of the extra-cellular ddC, the action of intra-cellular ddC continued to deplete the mtDNA to about 5% of control at 24 h (Fig. 5). After 24 hr, the mtDNA began to increase up to ~ 40% of control at 75 h post ddC removal (Fig. 5). All conditions exhibited similar cell growth rates (data not shown). The rate of mtDNA recovery was not affected by the over-expression of DNC (Two-way ANOVA, P>0.05).

Effect of over-expressing DNC on dTTP uptake and incorporation into isolated mitochondria

We studied whether over-expressing DNC in mitochondria could alter the rate of dNTP uptake and DNA synthesis in mitochondria. Results showed that the rates of dTTP uptake in mitochondria isolated from wt DNC induced and non-induced RKO cells were similar (Fig. 6A). The dTTP-uptake activity in isolated mitochondria can be inhibited by d4TTP in a dose related manner. However, there was no difference in the inhibitory
effect of d4TTP on dTTP-uptake in mitochondria isolated from wt DNC induced and
non-induced RKO cells. In addition, the rates of mtDNA synthesis were similar among
RKO control, RKO DNC induced, and non-induced cells (Fig 6B). Over-expressing DNC
did not change the inhibitory effect of d4TTP on the mtDNA synthesis.

Effect of down-regulated expression of DNC on mtDNA depletion and the lactic acid
production caused by dideoxynucleoside analogs (ddC, d4T, ddI)

We studied whether down regulating the expression of DNC could cause any
difference in mtDNA depletion caused by different dideoxynucleoside analogs. Since our
antibody was not sensitive enough to detect the endogenous level of DNC protein in
RKO cells, we used DNC over-expressing cells as a positive control for demonstrating
that siRNA could suppress the expression of DNC protein. Western blotting results
indicated that DNC could be suppressed by siRNA DNC by almost 90% but not by
siRNA CS (control sequence) (Fig. 7A). RT-PCR results showed that the mRNA of DNC
in RKO and DNC over-expressing cells could be down-regulated by siRNA DNC (Fig.
7B). The immunoflorescence results agreed with the results of Western blotting (Fig. 7C).
Confocal photographs showed that the green florescence emitted from anti-DNC
antibodies was reduced by almost 90% in the case of DNC over-expressing cells treated
with siRNA DNC but was not reduced by siRNA CS. Treatment of siRNA on RKO cells
did not affect cytochrome-c protein expression (confocal pictures not shown). It is
conceivable that the endogenous DNC protein expression could be suppressed
substantially.

The treated siRNA cells were tested for depletion of mtDNA and the lactic acid
production caused by dideoxynucleoside analogs (ddC, d4T, ddI). Results indicated that
the mtDNA depletion and induced lactic acid production (data not shown) caused by ddC, d4T and ddI were not affected by the treatment of siRNA DNC which could down-regulate DNC protein effectively. (Fig. 8A)

Effect of down-regulating the expression of DNC on dTTP uptake into isolated mitochondria

We also studied whether down-regulating DNC in mitochondria could alter the rate of dTTP uptake in isolated mitochondria. Results showed that the rates of dTTP uptake are similar in mitochondria isolated from RKO and DNC over-expressing cells treated with control sequence siRNA or target sequence siRNA (Fig. 8B).

Effect of down-regulating the expression of DNC and TK2 (thymidine kinase-2) on the mitochondria DNA content

We studied whether down-regulating DNC and TK2 could cause mitochondria DNA damage. Results indicated that using siRNA to down-regulate one or both of DNC and TK2 (Fig. 9A) did not affect the mitochondria DNA content (Fig. 9B) nor the action of dideoxynucleoside analogs in RKO cells (Fig. 10).
Mol Manuscript #7120

Discussion

DNC was suggested to play a key role in dNTP uptake into mitochondria. Our studies indicated this was probably not the case and the DNC properties were different from our previously described transport system. First, the activity of reconstituted DNC was cardiolipin dependent, optimized at 15% (w/w), by using phosphatidlycholine isolated from egg yolk but not from soy beans. Our dCTP transport system was not cardiolipin dependent and behaved better in liposomes prepared by phosphatidlycholine isolated from soy bean. Second, calcium inhibited the activity of DNC while calcium stimulated our dCTP transport system by 8-fold. Third, the Km values (600 µM to 5.6 mM) of dNTPs uptake were a hundred to a thousand fold higher than the Km (3 µM) of our dCTP transport system. Indeed, the Km of ddCTP and dCTP uptake in isolated mitochondria were about 1.82 µM and 0.82 µM respectively [Rossi, et al., 1999]. DNC may have a very low efficiency for the uptake of dNTPs into mitochondria.

The kinetic results of DNC reported by Dolce et al [Dolce, et al., 2001] also did not support the idea that DNC could function as a transporter of dNTPs or dNDPs in mitochondria, because the Km or Ki values of the nucleotides, except ADP, were well above the physiological concentration. The Ki value of ADP is 32µM that is only two folds higher than the Ki value of dADP (14µM) when competing with dATP with a Km of 100µM. However, the intracellular concentration of ADP is a hundred to a thousand fold higher than that of dADP or dNTP. Therefore, it is unlikely that DNC functions as the transporter of dNTP or ddNTP in mitochondria.
The results obtained from the reconstitution experiments *in vitro* may not reflect the behavior of the protein in cells. This could be due to non-optimum re-naturing conditions in the reconstitution experiments, the requirement for post translational modification of proteins, or the lack of other proteins necessary for action. We further studied the relationship between the expression levels of DNC and the action of anti-HIV dideoxynucleoside analogs on the mtDNA depletion inside the cells.

According to our previous reports, ddCTP is formed in the cytoplasm and is transported into mitochondria. If DNC can transport ddCTP into the mitochondria and the incorporation of ddCTP as a chain terminator can cause DNA depletion, the over-expression of DNC is likely to increase the uptake of ddCTP into mitochondria and the depletion of mtDNA. Increased expression of wt DNC protein, however, could not sensitize RKO cells or HepG2 cells (data not shown) to mtDNA depletion caused by ddC, d4T and ddI. Increased lactic acid production is regarded as the product of compensatory glycolysis that results from inhibition of mitochondria oxidative phosphorylation caused by the above dideoxynucleoside analogs. Our results indicated that lactic acid production was not affected by the over-expression of DNC.

We also studied whether the over-expression of DNC protein could affect the ability of mtDNA to recover from depletion caused by ddC. The lack of recovery in the first 75 h after ddC removal could be due to the uptake of the remaining cytoplasmic ddCTP or the time required to remove ddC from terminated mtDNA. If dNTPs or dNDPs uptake was the rate limiting step in mtDNA replication and over-expression of DNC could help the uptake of dNTPs or dNDPs into mitochondria for the repair processes to happen, the recovery rate of mtDNA should be faster. Our results demonstrated that over-
expression of DNC did not affect the dynamics of mtDNA content after removing the
extra-cellular ddC. The remaining ddC inside the cells continued to cause similar mtDNA
depletion under both non-induced and DNC-induced conditions. The time and rate of
mtDNA rebound were also similar under all conditions.

When we examined whether the dTTP uptake in mitochondria had been changed
by over-expression of DNC, we found that the induction of DNC did not increase the
dTTP uptake or DNA synthesis in isolated mitochondria. Moreover, the inhibitory effect
of d4TTP on the dTTP uptake and DNA synthesis in isolated mitochondria were not
affected by the over-expression of DNC.

At this point we could not discount the effect of DNC on transport completely,
due to the possibility that the intrinsic level of DNC protein could already be well above
the rate limiting level. We, therefore, down-regulated the DNC expression level by using
siRNA. Results showed that cells with the down-regulated DNC cells did not become
more resistant to these dideoxynucleoside analogs. The results on studies of the over and
under expression in tandem suggested that that DNC could not be the transporter
associated with the depletion of the mtDNA caused by these dideoxynucleoside analogs,
since even the knock-down DNC cells did not have mtDNA damage. The ratio of
mtDNA and genomic DNA in over-expressed DNC and down-regulated DNC cells were
similar. However, we cannot rule out the possibility of DNC being involved in
transporting dNTPs or dNDPs. The salvage pathway which is carried out by
deoxyguanosine kinase (dGK), thymidine kinase-2 (TK2), dNMP kinase and dNDP
kinase can supply enough dNTPs for mtDNA synthesis [Saada, et al., 2001; Mandel, et
al., 2001]. Therefore, we isolated mitochondria from down-regulated DNC (siRNA
treated) cells to study dNTPs uptake into mitochondria. We found that dTTP uptake in isolated mitochondria were not affected by down-regulating the DNC expression. Furthermore, we used siRNA to lower both DNC and TK2 expression. TK2 has been shown to play a key role in phosphorylating dC and dT [Wang, et al., 1999]. If we shut down TK2, mtDNA synthesis will solely depend on the importing of dNTP or dNDP from the cytoplasm. Our results indicated that mtDNA content and the action of dideoxynucleoside analogs on mtDNA depletion was not affected by down-regulation of DNC and TK2 expression (Fig. 9 and 10), again suggesting that DNC could not be the key transporter for dNTP or dNDP uptake into mitochondria.

In summary, our findings do not support the postulate that DNC could be associated with the mtDNA depletion caused by the dideoxynucleoside analogs, ddC, d4T and ddI, or that DNC can act as a dNTP transporter into mitochondria. The mitochondrial transporter(s) for deoxynucleoside triphosphate and dideoxynucleoside triphosphate analogs remains to be discovered. Based on the evidence that DNC does not appear to affect the mitochondria potential, mitochondrial Ca\(^{2+}\) storage, reactive oxygen species of cells and cellular growth, its function warrants further clarification.
ACKNOWLEDGMENT

We thank Susan Grill, Ginger E. Dutschman and Eric James for the critical reading of the manuscript.
References

Bogenhagen D, Clayton DA (1974) The number of mitochondrial
deoxyribonucleic acid genomes in mouse L and human HeLa cells. Quantitative


Chen CH and Cheng YC (1989) Delayed cytotoxicity and selective loss of
mitochondrial DNA in cells treated with the anti-human immunodeficiency virus

Chen CH and Cheng YC (1992) The role of cytoplasmic deoxycytidine kinase in
the mitochondrial effects of the anti-human immunodeficiency virus compound, 2',3'-

immunodeficiency virus nucleoside analogs on mitochondrial DNA and its

human mitochondrial deoxynucleotide carrier and its role in the toxicity of nucleoside

Elpeleg O, Mandel H, and Saada A (2002) Depletion of the other genome-

Highly efficient DNA synthesis in isolated mitochondria from rat liver. *Nucleic Acids
Res* **22**:1861-1865.


Footnotes

a. This work was supported in part by Grant no. R01-A138204 from the National Institutes of Health.

b. Dr. Yung-chi Cheng, Department of Pharmacology, Yale University School of Medicine, New Haven, CT 06520. Tel.: 203-785-7120; Fax: 203-785-7129; E-mail: cheng.lab@yale.edu
Legends for Figures

Fig. 1. Dependence of the dCTP uptake on the cardiolipin and cholesterol content in DNC-proteoliposomes formed by using phosphatidylcholine purified from egg yolk (■) or soy bean (▲). Uptake was initiated by the addition of 1 mM [α-32P] dCTP for 2 min. The rest of the procedures were the same as described in “Materials and Methods”.

Fig. 2. Effect of divalent metal ions on dCTP uptake activity of DNC.

Fig. 3. A. Expression of DNC protein in different cell lines. Cell lysates from different DNC inducible cell lines grown with or without doxycycline, 3µg/ml for 72h were prepared as described in "Materials and Methods." The cell lysates were analyzed by Western blotting. Top bands were detected by anti-actin monoclonal antibody and used as internal control; bottom bands were detected by anti-DNC monoclonal antibody. B. Sub-cellular localization of DNC protein of RKO-DNC cell lines (400X magnification). Cells with or without doxycycline, 3 µg/ml for 72h were fixed, immunofluorescently stained first with anti-DNC monoclonal antibody and second with anti-mouse IgG-FITC antibody, and mitochondria were counterstained with mito-tracker as described in "Materials and Methods." green indicates DNC; red indicates mitochondria.

Fig. 4. The inhibitory effect of dideoxynucleoside analogs, ddC, d4T and ddI on the mtDNA content (panel A) and the lactic acid production (panel B) of RKO cells. After doxycycline was removed from culture medium for 72 h for DNC induction, cells were treated by dideoxynucleoside analogs for 4 days. Two-way ANOVA analysis or student
t-test were used to determine if there was any significant difference between the results. The rest of the procedures were the same as described in “Materials and Methods”.

Fig 5. Recovery of mtDNA of RKO cells. Cells were pretreated with ddC at 20 µM for 4 days. The content of mtDNA was measured at different time points after cells were re-seeded in ddC free medium. The rest of the procedures were the same as described in “Materials and Methods”.

Fig. 6. The uptake (upper panel) and incorporation (lower panel) of dTTP into isolated mitochondria from RKO cells. The rest of the procedures were the same as described in “Materials and Methods”.

Fig. 7. siRNA-mediated down-regulation of DNC in RKO cells. A, the immunoblot shows the DNC content in the cells, and actin has been used as an internal control. B, RT-PCR shows the RNA expression of DNC in the cells, and actin has been used as an internal control. C, immunofluorescence of siRNA-mediated down-regulation of DNC in the DNC expressed RKO cells (400X magnification). The rest of the procedures were the same as described in “Materials and Methods”.

Fig. 8. The effects of down-regulation of DNC. A, The inhibitory effect of dideoxynucleoside analogs, ddC, d4T and ddI on the mtDNA content of RKO cells pre-treated with siRNA. After doxycycline was removed from culture medium for 72 h for DNC induction, pre-treated-siRNA cells were treated with dideoxynucleoside analogs for 4 days. Two-way ANOVA analysis was used to determine if there was any significant
Mol Manuscript #7120

difference between the results.  

B, The uptake of dTTP into isolated mitochondria from siRNA pretreated RKO and DNC over-expressing cells. The rest of the procedures were the same as described in “Materials and Methods”.

Fig. 9. The effect of down-regulation of DNC and TK2 on mitochondria DNA content.  

A, RT-PCR shows for the expression of DNC and TK2 in RKO cells and DNC cells after siRNA treatment.  

B, The relative mitochondria DNA in RKO cells and DNC cells (4 days) after siRNA treatment. The rest of the procedures were the same as described in “Materials and Methods”.

Table 1. Comparison of kinetic data of reconstituted proteoliposome with or without cholesterol.

<table>
<thead>
<tr>
<th></th>
<th>PC(^{a+15}%) CL(^{b})</th>
<th>PC+15%CL+10% Cholesterol</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Km, mM</td>
<td>Vmax, n mole/min/mg</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dCTP</td>
<td>3.2±0.6</td>
<td>45±5.9</td>
</tr>
<tr>
<td>dCTP/iADP(^{d})</td>
<td>2.1±0.4</td>
<td>18±3.6</td>
</tr>
<tr>
<td>dATP</td>
<td>1.1±0.3</td>
<td>11±1.2</td>
</tr>
<tr>
<td>dATP/iADP</td>
<td>1.7±0.4</td>
<td>7±0.5</td>
</tr>
<tr>
<td>dTTP</td>
<td>0.8±0.2</td>
<td>4.9±0.8</td>
</tr>
<tr>
<td>dTTP/iADP</td>
<td>0.6±0.2</td>
<td>3.2±0.6</td>
</tr>
</tbody>
</table>

\(^{a}\) Egg yolk phosphatidylcholine  
\(^{b}\) CL, cardiolipin  
\(^{c}\) Km values were derived from a Lineweaver-Burk plot. V\(_{max}\) values were calculated using the Michaelis-Menton equation. Values are presented as mean ± SD from at least three independent experiments.  
\(^{d}\) iADP, 10mM internal ADP
Fig. 1

![Graph showing the relationship between dCTP uptake and various lipid concentrations. The graphs display data points with error bars indicating variability. The x-axis represents lipid concentrations (cardiolipin and cholesterol) ranging from 0 to 20% (w/w), while the y-axis represents dCTP uptake in nmol/min/mg. The graphs illustrate the effect of lipid composition on dCTP uptake, with some conditions showing an increase in uptake with higher lipid concentrations.](molpharm.aspetjournals.org)
Fig. 2

[Bar graph showing dGTP uptake (nmol/mg/min) for different metal chlorides at 0.5mM and 2mM concentrations. The x-axis represents control, BaCl₂, CaCl₂, CoCl₂, CuCl₂, MgCl₂, MnCl₂, and ZnCl₂. The y-axis shows the uptake in nmol/mg/min.]
Fig. 3

A

<table>
<thead>
<tr>
<th></th>
<th>RKO</th>
<th>DNC</th>
<th>DNC-G177A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dox</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Actin</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DNC</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

B

<table>
<thead>
<tr>
<th></th>
<th>Mito-tracker</th>
<th>Anti-DNC</th>
<th>Merge</th>
</tr>
</thead>
<tbody>
<tr>
<td>RKO + dox</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RKO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DNC + dox</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DNC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DNC-G177A + dox</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DNC-G177A</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fig. 4

A

Relative Mitochondria DNA

ddC (µM)

d4T (µM)

ddl (µM)

B

Relative Lactic acid

RKO  DRC  DRC-G177A  RKO  DRC  DRC-G177A  RKO  DRC  DRC-G177A
Fig. 5
Fig. 7

A

<table>
<thead>
<tr>
<th>siRNA</th>
<th>RKO</th>
<th>DNC</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>CS</td>
<td>DNC</td>
</tr>
</tbody>
</table>

Actin

DNC

B

| DNC | Actin |

C

| Mito-tracker | Anti-DNC | Merge |

siRNA CS

siRNA DNC
Fig. 8

A

B

Relative Mitochondrial DNA

2.0
1.5
1.0
0.5

0.0

0 25 50 75 100

25 50 75 100

0 25 50 75 100

RKO cells

DNC cells

dDC (µM)
d4T (µM)
ddi (µM)

- CS DNC

- CS DNC sRNA

dTP uptake

photon/mg
Fig. 9

A

<table>
<thead>
<tr>
<th>siRNA</th>
<th>RKO cells</th>
<th>DNC cells</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CS CS DNC TK2 TK2</td>
<td>CS CS DNC TK2 TK2</td>
</tr>
</tbody>
</table>

TK2

DNC

Actin

B

Relative Mitochondria DNA Content

- $\text{CS}$
- $\text{DNC}$
- $\text{TK2}$
- $\text{TK2}$

RKO cells

DNC cells