UvA-DARE (Digital Academic Repository)

The multidrug resistance reverser verapamil with cellular P-glycoprotein-mediated pumping of daunorubicin as a non-competing substrate.

Spoelstra, E.C.; Westerhoff, H.V.; Pinedo, H.M.; Dekker, H.; Lankelma, J.V.

DOI

[10.1111/j.1432-1033.1994.tb18748.x](https://doi.org/10.1111/j.1432-1033.1994.tb18748.x)

Publication date

1994

Published in

European Journal of Biochemistry

[Link to publication](#)

Citation for published version (APA):

Spoelstra, E. C., Westerhoff, H. V., Pinedo, H. M., Dekker, H., & Lankelma, J. V. (1994). The multidrug resistance reverser verapamil with cellular P-glycoprotein-mediated pumping of daunorubicin as a non-competing substrate. *European Journal of Biochemistry*, 221, 363-373. <https://doi.org/10.1111/j.1432-1033.1994.tb18748.x>

General rights

It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations

If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: <https://uba.uva.nl/en/contact>, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.

The multidrug-resistance-reverser verapamil interferes with cellular P-glycoprotein-mediated pumping of daunorubicin as a non-competing substrate

Ellen C. SPOELSTRA¹, Hans V. WESTERHOFF², Herbert M. PINEDO¹, Henk DEKKER¹ and Jan LANKELMA¹

¹ Department of Medical Oncology, Free University Hospital, Amsterdam, The Netherlands

² Division of Molecular Biology, The Netherlands Cancer Institute and E. C. Slater Institute, Biocentrum, University of Amsterdam, Amsterdam, The Netherlands

(Received July 6/November 3, 1993) – EJB 93 1002/1

We examined P-glycoprotein-mediated verapamil transport, using two drug-sensitive and multidrug resistant cell-line couples, i.e. A2780, 2780^{AD} and SW-1573, SW-1573/1R500. The interaction of ³H-labeled verapamil with cells was measured using a flow-through system. The verapamil-containing medium was pumped over the cells and monitored on-line for radioactivity. In the P-glycoprotein-expressing cells, verapamil accumulation was increased by vinblastine and some known multidrug resistant (MDR) modifiers. Subsequent removal of these modifiers caused release of verapamil into the medium against a verapamil concentration gradient. In this manner, we obtained evidence that verapamil is actively transported by the MDR-related P-glycoprotein.

Using the flow-through system, we also exposed the cells to flowing culture medium containing daunorubicin, and measured the inhibition of daunorubicin efflux by verapamil. We found that, although the active efflux of daunorubicin was maximally blocked by verapamil short-term, longer-term active efflux of daunorubicin resumed. At a daunorubicin concentration in the flowing medium of 5 µM, increasing the verapamil concentration resulted in the same short-term effects, but in a significantly longer period of a maximal inhibition of daunorubicin efflux from the cells. At a daunorubicin concentration of 20 µM, increasing the verapamil concentration affected neither the short-term nor the long-term effects. These and other observations are in agreement with a model in which daunorubicin and verapamil are non-competing substrates for P-glycoprotein.

In conclusion, we obtained evidence that verapamil is actively transported by the MDR-related P-glycoprotein and that verapamil and daunorubicin are non-competing substrates for P-glycoprotein. Consequently, the effectiveness of verapamil as an MDR antagonist may be compromised because it is extruded by P-glycoprotein.

A major problem in the treatment of cancer patients is the development of resistance against natural-product anticancer drugs, such as anthracyclines and vinca alkaloids. *In vitro* cells have also been made resistant to such anticancer drugs. This resistance is called multidrug resistance (MDR). It is usually associated with a high-molecular-mass P-glycoprotein in the cellular plasma membrane [1, 2]. A common assumption has been that this protein acts as an energy-dependent efflux pump, which maintains a low intracellular drug concentration in MDR cancer cells [2, 3]. In 1981 Tsuruo et al. [4] reported that verapamil potentiated the cytotoxic activity of vincristine in the MDR murine leukemia cell line P388. Since that time, many compounds with different structural features have been found which reverse P-glycoprotein associated MDR [5, 6]. At a high concentration, verapamil is one of the compounds with the strongest *in vitro* effect on the vincristine or doxorubicin cytotoxicity in resistant mouse and human tumor cells [7, 8]. The main problem

for clinical use of MDR modulators is the inability to show clear cytotoxic effects at the relatively low concentrations of the modulator that can be achieved clinically [9]. Another problem is that even relatively high concentrations of the MDR modulator usually do not completely reverse MDR; in particular, they do not restore the accumulation of the MDR-related drugs daunorubicin or doxorubicin [10]. The aim of our study was to examine the possible mechanisms underlying these two problems, with special emphasis on the cellular plasma membrane transport of verapamil into intact cells.

In photoaffinity-labeling studies, competition of verapamil with a vinblastine photoactive analogue for binding P-glycoprotein has been shown [11, 12]. Binding of photoactive analogues of verapamil was totally or partly inhibited by some known MDR modifiers (Cremophor EL, 100%) or MDR-related drugs (doxorubicin or vincristine in 5000-fold excess medium concentration, reduced the amount of radio-labeling by 67% or 78%, respectively) [13, 14]. If verapamil is a competing inhibitor of the pumping of the anticancer drug employed, the effectiveness of verapamil might be compromised at high (or lower) concentrations of daunorubicin because of the increase in intracellular drug concentration ensuing from partial P-glycoprotein inhibition. Consequently,

Correspondence to J. Lankelma, Department of Medical Oncology, Free University Hospital, De Boelelaan 1117, NL-1081 HV Amsterdam, The Netherlands

Abbreviation. MDR, multidrug resistant/resistance.

it is of interest to examine whether verapamil is a competing or a non-competing MDR modifier.

Verapamil increased cellular ATP consumption and lactate formation specifically in P-glycoprotein-containing MDR cells [15]. One possible explanation for these observations was that this resistance modifier might be transported by an ATP-hydrolysis dependent, P-glycoprotein-mediated, mechanism [15]. P-glycoprotein was indeed identified as a specific acceptor for photoaffinity analogues of verapamil in a Chinese hamster lung cell line resistant to vincristine [16] as well as in a human myelogenous leukemia cell line [13]. If verapamil is removed from the cell by P-glycoprotein, its effectiveness as a reversing agent might decrease. Decreased verapamil accumulation and increased efflux of verapamil have been reported for MDR cells [3, 13, 17–20]. However in the drug-sensitive and MDR cell lines EHR2 and EHR2/DNR+, Sehested et al. [21] found no MDR-related reduction in verapamil accumulation, nor did they find an increased verapamil accumulation after energy depletion. Although some studies indicate a P-glycoprotein-mediated export of verapamil [3, 13, 17–20], which may account for the low effectiveness of the modifier, to date, it has not yet been proven that such a mechanism exists.

Here we examine these two possible explanations for the problems, using verapamil as an MDR antagonist *in vivo*. It was essential that this examination was performed in the physiological context of the intact cell. To this purpose, we employed the flow-through system [22–24]. We studied the transport of verapamil in two highly resistant cell lines, the human ovarian cancer cell line 2780^{AD} and the human lung cancer cell line SW-1573/1R500, and in their drug-sensitive counterparts A2780 and SW-1573. Cremophor EL, bepridil, vinblastine, daunorubicin, and amiodarone were used as known MDR modifiers or MDR-related drugs [14, 25–28]. Interpretation of the results obtained with intact cells was complicated because more than one process is involved in determining drug accumulation. To facilitate the interpretation, we developed a quantitative model of a cell with a passive membrane permeability parallel to an active pump for two substances.

Our results suggest that verapamil is a substrate for the P-glycoprotein but as such it does not compete with daunorubicin. Consequently, the low effectiveness by which verapamil reverses the MDR phenotype may not be caused by its competition with a certain anticancer drug, but by removal of verapamil by P-glycoprotein from the cell.

MATERIALS AND METHODS

Chemicals

Verapamil/HCl and 2-deoxy-d-glucose were obtained from Sigma Chemical Co. Daunorubicin/HCl was purchased from Specia. [*N*-³H-methyl]verapamil hydrochloride (specific activity 70 Ci/mmol) was obtained from New England Nuclear. Cremophor EL was a gift from Sandoz. Bepridil monohydrochloride monohydrate, β -[(2-methyl-propoxy)-methyl]-*N*-phenyl-*N*-(phenylmethyl)-1-(pyrrolidine)ethanamine (ORG 5730) was obtained from Organon International BV. Sodium azide and doxorubicin were obtained from Baker Chemicals and Laboratoire Roger Bellon, respectively. Vinblastine sulphate was obtained from Eli Lilly and progesterone was obtained from Sigma.

Cells

The source and culture conditions of the wild-type human ovarian carcinoma cell line A2780, its resistant subline 2780^{AD} and of the wild-type human non-small-cell lung cancer cell line SW-1573 and its resistant subline SW-1573/1R500, have been described before [28–31]. The cells were checked for mycoplasma by the mycoplasma T. C. rapid-detection system with a ³H-labeled DNA probe from Gen-Probe Inc. They were found to be negative.

Determination of changes of verapamil accumulation

Verapamil accumulation was determined in various cell lines, using a flow-through system and a flow-through radioactivity detector. The flow-through system has been described in detail before [22, 24, 32]. Basically, a monolayer of approximately 10⁷ cells present on the bottom of a chamber (surface 50 cm², height 0.1 mm) was perfused with drug-containing medium A (Dulbecco's modified minimal essential medium without bicarbonate and phenol red, but containing 20 mM Hepes, 5% fetal bovine serum, 5.6 mM glucose and 4 mM glutamine. The perfusion medium (pH 7.3) was passed over the cells at a constant flow rate of 200 μ l/min, at 37°C. Then ³H-labeled verapamil was added to the perfusion medium (0.1 μ M verapamil, containing 0.05 nM ³H-labeled verapamil) and cells accumulated verapamil until the steady-state was reached, i.e. when the concentration of verapamil at the output of the flow-through system attained the same level as the input concentration. The extracellular concentrations of verapamil were measured on-line at the output of the flow-through system by measuring the radioactivity every 6 s with a window of 0–20 kV, in a radioactivity flow detector (Flo-one/beta, Radiomatic Instruments & Chemicals Co.). Using a flow cell of 0.5 ml, Pico-aqua scintillation liquid (Packard Instruments) at a flow rate of 800 μ l/min, the data were collected and processed with the software programme A250-1,6 (Radiomatic Instruments & Chemicals Co.). The verapamil input concentration in the perfusion medium was checked by measuring radioactivity in the same manner as described above, but the cell-containing flow-through system in between was omitted.

Effects of various modifiers or drugs on the accumulation of verapamil

When extracellular steady-state concentrations of verapamil had been reached, pulse injections (15 μ l) of the modifying agent were introduced into the flowing medium via an HPLC injection valve. This caused a band of modifier-containing medium to move over the cells (each pulse diluted into a volume of 50–200 μ l). A series of pulse injections of modifier was administered at time intervals of 60 s in order to approach a one-step rise in the concentration of modifier and a high concentration of modifier was used in order to obtain maximal effects. Average concentrations of modifying agents or drugs in the perfusion medium to which the cells were exposed were 0.4–1.4 mg/ml for Cremophor EL, 30–100 μ M for daunorubicin, 20–70 μ M for bepridil, 15–60 μ M for vinblastine and 20–70 μ M for amiodarone. The increased cellular verapamil accumulation was represented by a decrease of the level of radioactivity in the medium at the outlet of the system. At the end of the experiments, the same series of modifier pulses were repeated as a control for each cell line used. No differences were found compared to

the effects of the same modifiers observed at an earlier stage of the experiment. Then the cells were harvested and counted in a hemocytometer. The viability of the cells (routinely > 90%) was determined by the trypan blue exclusion test.

Effects of verapamil on the cellular accumulation of daunorubicin

Using the flow-through system, daunorubicin was added to the perfusion medium instead of verapamil. Daunorubicin concentrations were determined by on-line measurement of fluorescence or light absorption as described elsewhere [22]. When the daunorubicin concentration in the effluent became constant, various concentrations of verapamil were added to the daunorubicin-containing perfusion medium. We used an energy-depleting medium C, i.e. medium A without glucose but supplemented with 10 mM sodium azide, 6.1 mM deoxyglucose and 5% fetal bovine serum that had been dialyzed for 24 h against 1 mM KH_2PO_4 , pH 7.4, using a Visking-30 dialysis tube, 1:200 by vol. (Radiometer). This caused a decrease of the cytosolic pH of about 0.3 [23]. The drop in pH could be compensated by the addition of 40 mM methylamine to medium C (unpublished results). Therefore, in order to measure the effects of energy depletion without altering intracellular cytosolic pH values, we used medium C supplemented with 40 mM methylamine. The increased rate of daunorubicin accumulation in the cells, caused by the verapamil addition or a shift to medium C, was reflected by a decrease in the daunorubicin concentration in the eluent at the outlet of the flow-through system. From the short-term maximal decrease of the daunorubicin medium concentration, the net inward accumulation rate was calculated according to:

$$v_{iw,s} = F/N \cdot (D^{(i)} - D_s^{(ib)}), \quad (1)$$

where $v_{iw,s}$, F , $D^{(i)}$, $D_s^{(ib)}$ and N represent the short-term maximal net inward accumulation rate of daunorubicin ($\text{mol} \cdot \text{min}^{-1} \cdot \text{cell}^{-1}$), the flow rate (l/min), the medium concentration of daunorubicin at the input of the flow-through system (mol/l), the minimum extracellular daunorubicin concentration at the output of the flow-through system attained after verapamil addition or medium substitution (mol/l), and the number of cells, respectively. Previously, we demonstrated the specificity of the verapamil effects for P-glycoprotein in several human wild-type colon cell lines, i.e. HT29, SW1116 and COLO 320, the murine colon cell line C-26 and, for the drug-sensitive/MDR human ovarian cancer cell line couple A2780/2780^{AD} [22]. Therefore, the disturbed equilibrium between inward and outward transport of daunorubicin after addition of verapamil is most likely a result of the inhibition of the P-glycoprotein-mediated efflux pump. If sufficient verapamil was added to completely inhibit the pump, then

$$v_{iw,s} = -v_{\text{pump,ss}}, \quad (2)$$

where $v_{\text{pump,ss}}$ refers to the pump flux in the steady-state situation before addition of verapamil.

Modelling the transport of daunorubicin after addition of verapamil

Our ultimate model featured non-competitive inhibition of daunorubicin transport by verapamil. The overall transport of daunorubicin across the cell membrane was considered to result from (a) passive transport of the uncharged form of the

drug and (b) the active efflux of the drug. The net inward flux of daunorubicin was described as

$$v_{iw} = (k \cdot D^{un}) - (k \cdot X^{un}) - v_{\text{pump}}, \quad (3)$$

where v_{iw} , k , D^{un} , X^{un} and v_{pump} represent the net inward cellular accumulation rate of daunorubicin ($\text{mol} \cdot \text{min}^{-1} \cdot \text{cell}^{-1}$), passive permeation coefficient ($\text{l} \cdot \text{min}^{-1} \cdot \text{cell}^{-1}$), the extracellular uncharged daunorubicin concentration (mol/l), the intracellular free cytosolic uncharged daunorubicin concentration (mol/l), and the active pump efflux rate ($\text{mol} \cdot \text{min}^{-1} \cdot \text{cell}^{-1}$), respectively. The terms $k \cdot D^{un}$ and $k \cdot X^{un}$ represent the passive influx of daunorubicin ($\text{mol} \cdot \text{min}^{-1} \cdot \text{cell}^{-1}$) and the passive efflux of daunorubicin ($\text{mol} \cdot \text{min}^{-1} \cdot \text{cell}^{-1}$), respectively. We calculated the concentration of the internal free cytosolic daunorubicin before addition of the inhibitor, using this kinetic model for daunorubicin transport. The assumptions underlying this equation, have been discussed elsewhere [23].

We examined the case in which there is no competition between daunorubicin and verapamil for P-glycoprotein-mediated pumping, but where verapamil inhibits the pumping of daunorubicin. In the rapid-binding case (taking the simplest case), one derives for the rate at which daunorubicin should be pumped [23, 33, 34]:

$$v_{\text{pump},X} = \frac{[V_{\text{max},X}^{\text{ow}} \cdot (X/K_{m,X})^h] - [V_{\text{max},D}^{\text{iw}} \cdot (D/K_{m,D})^h]}{[1 + (X/K_{m,X})^h + (D/K_{m,D})^h] \cdot [1 + Y/K_{m,Y} + I/K_{m,I}]} \quad (4)$$

For the rate at which verapamil is pumped,

$$v_{\text{pump},Y} = \frac{(V_{\text{max},Y}^{\text{ow}} \cdot Y/K_{m,Y}) - (V_{\text{max},I}^{\text{iw}} \cdot I/K_{m,I})}{1 + Y/K_{m,Y} + I/K_{m,I}} \quad (5)$$

Eqn (5) purports that daunorubicin does not affect the pumping of verapamil. In Eqn (4), $v_{\text{pump},X}$ and $V_{\text{max},X}^{\text{ow}}$ have been defined as the P-glycoprotein-mediated active pump efflux rate for daunorubicin ($\text{mol} \cdot \text{min}^{-1} \cdot \text{cell}^{-1}$), and the maximal pump rate for daunorubicin across the plasma membrane from the cytosol into the external medium ($\text{mol} \cdot \text{min}^{-1} \cdot \text{cell}^{-1}$), respectively. X and $K_{m,X}$ correspond to the cytosolic concentration of free daunorubicin (mol/l) and the Michaelis-Menten constant for the P-glycoprotein-mediated efflux of daunorubicin (mol/l), respectively. The superscript h corresponds to a co-operativity index for daunorubicin according to T. L. Hill [35]. $V_{\text{max},D}^{\text{iw}}$, D and $K_{m,D}$ are the maximal P-glycoprotein-mediated influx rate of daunorubicin from the external medium into the cytosol ($\text{mol} \cdot \text{min}^{-1} \cdot \text{cell}^{-1}$), the external concentration of daunorubicin (mol/l) and the corresponding Michaelis-Menten constant (mol/l). Y , $K_{m,Y}$, I and $K_{m,I}$ represent the cytosolic free verapamil concentration (mol/l), the Michaelis-Menten constant for the P-glycoprotein-mediated efflux of verapamil (mol/l), the external concentration of verapamil (mol/l), and the Michaelis-Menten constant for the P-glycoprotein-mediated influx of verapamil (mol/l), respectively. In Eqn (5), $v_{\text{pump},Y}$, $V_{\text{max},Y}^{\text{ow}}$ and $V_{\text{max},I}^{\text{iw}}$ represent the P-glycoprotein-mediated active pump efflux rate for verapamil ($\text{mol} \cdot \text{min}^{-1} \cdot \text{cell}^{-1}$), the maximal pump rate for verapamil across the plasma membrane from the cytosol into the external medium ($\text{mol} \cdot \text{min}^{-1} \cdot \text{cell}^{-1}$) and the maximal P-glycoprotein-mediated influx rate for verapamil from the external medium into the cytosol ($\text{mol} \cdot \text{min}^{-1} \cdot \text{cell}^{-1}$), respectively. In the alternative model where there is competition between daunorubicin and verapamil, the denominators of Eqn (4) and Eqn (5) were replaced by $1 + (X/K_{m,X})^h + (D/K_{m,D})^h + Y/K_{m,Y} + I/K_{m,I}$ [33].

In order to simulate the time-dependent change of the total extracellular daunorubicin concentration, or the change of the net accumulation rate of daunorubicin after addition of verapamil, we integrated a set of coupled differential equations. These equations were derived from Eqn 3, in which D^{un} and X^{un} were replaced by the total, i.e. protonated plus unprotonated concentrations of the extracellular daunorubicin and intracellular daunorubicin, respectively, in order to simplify the equation. This replacement was justified by using the passive leakage constants for the total daunorubicin concentrations at a known pH.

$$\frac{dX}{dt} = \frac{v_{iw,D}}{V_D} = \frac{k \cdot D - k' \cdot X - v_{pump,X}}{V_D} \quad (6)$$

$$\frac{dY}{dt} = \frac{v_{iw,I}}{V_I} = \frac{k' \cdot I - k' \cdot Y - v_{pump,Y}}{V_I} \quad (7)$$

In these equations, $v_{iw,D}$, $v_{iw,I}$, k' , V_D and V_I represent the net inward accumulation rate of daunorubicin ($\text{mol} \cdot \text{min}^{-1} \cdot \text{cell}^{-1}$), the net inward accumulation rate of verapamil ($\text{mol} \cdot \text{min}^{-1} \cdot \text{cell}^{-1}$), the passive permeation coefficient for verapamil ($\text{l} \cdot \text{min}^{-1} \cdot \text{cell}^{-1}$), the apparent intracellular, daunorubicin-accessible volume of a cell (l/cell), and the apparent intracellular, verapamil-accessible volume of a cell (l/cell), respectively. Most of the intracellular drug is not dissolved in the intracellular aqueous volume, but is bound to intracellular structures. Assuming that this binding is nonsaturated and in rapid equilibrium, it can be accounted for by attributing an extended apparent volume to the cell. Effects of changes in extracellular daunorubicin or verapamil concentrations as a result of cellular activities were neglected. After replacing the terms $v_{pump,X}$ and $v_{pump,Y}$ using Eqns 4 and 5, this set of coupled differential equations was numerically integrated, using the Mathematical Modelling System 'MLAB'.

RESULTS

Verapamil accumulation in parent A2780 and SW-1573 cells and their resistant counterparts

Using the flow-through system, the interaction between verapamil and cells which grow in monolayer was monitored on-line. In Fig. 1a and b, the verapamil concentration in the output medium is shown as a function of time, after adding verapamil to the influx medium. Fig. 1a gives the differences between the time-dependent verapamil concentrations obtained for the drug-sensitive human lung cancer cell line SW-1573 and its MDR counterpart SW-1573/1R500. In Fig. 1b, the differences between the graph obtained for the human ovarian cancer cell line A2780 and that for its resistant counterpart 2780^{AD} are shown. We interpret these data in terms of MDR specific differences in total verapamil accumulation. Steady-state verapamil concentrations were obtained after approximately 15 min using the MDR cell lines 2780^{AD} or SW-1573/1R500, and after 60–90 min using their drug-sensitive counterparts A2780 or SW-1573. From these data, the total verapamil accumulation/cell was obtained (see also Eqn 1) as:

$$Q = \frac{F}{N} \cdot \int_{t=0}^{t=t_{ss}} (P - P^u) dt. \quad (8)$$

Here Q , $t = 0$, $t = t_{ss}$, P and P^u represent the total verapamil accumulation/cell (mol/cell), the time required to pass the void volume after adding verapamil to the flowing me-

Fig. 1. The amount of verapamil, leaving the flow-through system after addition of verapamil to the influx medium, comparing two drug-sensitive/MDR cell line couples, i.e. SW-1573, SW-1573/1R500 and A2780, 2780^{AD}. Conditions: number of cells, approximately 5×10^6 ; cell chamber volume, 500 μl ; temperature, 37°C; pH, 7.3; perfusion medium flow rate, 200 $\mu\text{l}/\text{min}$; scintillation liquid flow rate, 800 $\mu\text{l}/\text{min}$; verapamil and ^3H -labeled verapamil were added to medium A at the indicated time (V_p , arrow), input concentration of verapamil, 0.1 μM . Integration according to Eqn (8) started at $t = 0$, i.e. after passage of the void volume. (a) Uptake graphs for verapamil, comparing SW-1573 and SW-1573/1R500 cells. (b) Uptake graphs for verapamil, comparing A2780 and 2780^{AD} cells.

dium, the time at which the steady-state was (virtually) reached, the medium concentration of verapamil at the inlet of the flow-through system (mol/l), and the time-dependent medium concentration of verapamil (mol/l) at the outlet of the flow-through system, respectively. The input concentration of verapamil was determined by taking a time average of the steady-state output concentration of verapamil. At an extracellular verapamil concentration of 0.1 μM , the accumulation of verapamil in the drug-sensitive cell lines A2780 and SW-1573 was significantly higher when compared to the accumulation of verapamil in the resistant cell lines 2780^{AD} and SW-1573/1R-500 (Student t -test $P < 0.01$). The total verapamil accumulation in the parent cell lines SW-1573 and A2780, corrected for the delay curve in the flow-through system without cells (volume of cells in the monolayer was less than 5% of the total volume of the flow-through system and, therefore, could be neglected), was $28 \pm 5 \text{ pmol} \cdot (10^6 \text{ cells})^{-1}$ and $73 \pm 14 \text{ pmol} \cdot (10^6 \text{ cells})^{-1}$, respectively (means $\pm$ SD from three and two independent experiments, respectively). No significant difference was found when we compared the uptake curve for the MDR cell lines SW-1573/1R500 or 2780^{AD} with the curve for the flow-through system without cells; at most $10 \text{ pmol} \cdot (10^6 \text{ cells})^{-1}$ verapamil accumulated

Fig. 2. Effects of series of pulses of Cremophor EL on the extracellular verapamil concentration ([Vp]), comparing the parent SW-1573 and A2780 cells with their MDR counterparts. Conditions: see Fig. 1; 8 injections of Cremophor EL (CrEL) with time intervals of 1 min in the time period as indicated. Concentration of Cremophor EL above the cells, 0.4–0.14 mg/ml. (a) The effects of Cremophor EL on the extracellular verapamil concentration, using SW-1573/1R500 cells. (b) The effects of Cremophor EL on the extracellular verapamil concentration, using 2780^{AD} cells. (c) The effects of Cremophor EL on the extracellular verapamil concentration, using SW-1573 cells. (d) The effects of CrEL on the extracellular verapamil concentration, using A2780 cells.

in these MDR cells. The ratio of verapamil accumulation in the drug-sensitive cells and the verapamil accumulation in their MDR counterparts proved to be at least 2.6 ± 0.2 and 7 ± 2 for SW-1573/SW-1573/1R500 and A2780/2780^{AD} cells, respectively.

Effects of various MDR modifiers or MDR-related drugs on the cellular verapamil accumulation

Changes of cellular verapamil accumulation, caused by adding various MDR modifiers or MDR-related drugs to the verapamil-containing flowing medium, were measured after the steady-state had been reached. These changes could be observed as changes in the verapamil medium concentration, which were measured at the outlet of the flow-through system. Fig. 2 shows that a series of pulse injections of the MDR modifier Cremophor EL [25] resulted in a decrease of the extracellular verapamil concentration for the cell lines 2780^{AD} and SW-1573/1R500. The extracellular verapamil concentration was only slightly affected for A2780 and SW-1573 cells. This indicates that the decrease depends on the presence of P-glycoprotein. When the Cremophor EL pulses

were washed out, an increase of the verapamil medium concentration *above the steady-state concentration* was observed. This indicates an efflux of the verapamil which had been taken up additionally during the presence of Cremophor EL. The effects of a series of pulses of daunorubicin, bepridil, vinblastine or amiodarone were examined for the MDR 2780^{AD} cell line (not shown). A significant decrease of the steady-state verapamil concentrations was obtained using vinblastine or amiodarone (20–25%) and only a small decrease was obtained, using bepridil (10–15%). In these experiments, daunorubicin caused no decrease in the steady-state verapamil concentrations. When drug-sensitive A2780 cells were used, daunorubicin, bepridil, vinblastine or amiodarone only increased the extracellular verapamil concentrations, possibly by competition for binding sites which are not MDR specific, or had no effect at all (not shown).

The dynamic response of the extracellular daunorubicin concentration to various verapamil medium concentrations

To examine whether verapamil is a competing or a non-competing substrate for P-glycoprotein-mediated daunorubicin transport, we studied the effects which variation in verapamil medium concentrations had on the daunorubicin uptake by the cells. We measured the fluorescence or light absorbance of daunorubicin instead of the radioactivity of verapamil. We described how the cellular daunorubicin accumulation rate can be calculated from disturbance of the steady-state between inward and outward transport of daunorubicin, induced by the MDR modifiers (Eqn 1). This was presumably caused by an inhibition of the P-glycoprotein-mediated efflux by these modifiers [22].

In Fig. 3a, adding 8 μ M verapamil to the daunorubicin-containing flowing medium resulted in a decrease of the extracellular daunorubicin concentration of the medium above the cell line 2780^{AD}. This effect was not found for its drug-sensitive counterpart A2780 (not shown). This is an indication of MDR specificity (see also [22, 24]). We changed the concentration of verapamil in the flowing medium, which contained 5 μ M daunorubicin and found that the maximal initial accumulation rate of daunorubicin (maximal depth of the dip) after adding 32 μ M verapamil differed only 11% from the rate obtained with 16 μ M verapamil (Fig. 4). Increasing the verapamil concentrations over 30–100 μ M caused the maximal initial accumulation rate of daunorubicin to increase by only 4% (Fig. 3b). We measured the rise of the verapamil concentration at 5 μ M daunorubicin, using ³H-labeled verapamil as mentioned above (not shown). When the depth of the daunorubicin signal was at its maximum, the verapamil concentration had attained at least 70% of its maximum, at concentrations of verapamil of 4 μ M or higher (Fig. 3a and b).

We compared the effects of 50 μ M verapamil and the effects after complete inhibition of P-glycoprotein by energy depletion without changing the intracellular pH (addition of medium C supplemented with 40 mM methylamine; see Materials and Methods) and we found the same maximal initial accumulation rates of daunorubicin (Fig. 3c). These results suggest that the P-glycoprotein-mediated initial efflux is virtually completely blocked by 30 μ M verapamil.

In contrast, at a daunorubicin concentration of 5 μ M in the flowing medium, the accumulation rate of daunorubicin 30 min after 30 μ M verapamil had been added, differed significantly from the accumulation rate 30 min after 100 μ M

Fig. 3. Effects of various verapamil concentrations or energy depletion on the extracellular daunorubicin concentration, using 2780^{AD} cells. Conditions: see Fig. 1; extracellular daunorubicin concentration ([DN]), 5 μM ; verapamil (Vp) was added to the drug-containing perfusion medium at the indicated time point. (a) The effects of 8 μM verapamil on the extracellular daunorubicin concentration. (b) The effects of 30 μM and 100 μM verapamil on the extracellular daunorubicin concentration. Change of daunorubicin containing medium supplemented with various concentrations of verapamil was performed after allowing the cells to efflux the extra accumulated daunorubicin, using medium without verapamil. Two graphs are projected in one time axis. (c) The effects of 50 μM verapamil and subsequently 375 μM verapamil on the extracellular daunorubicin concentration (—) or the effects of energy depleting medium (medium C), containing 40 mM methylamine on the extracellular daunorubicin concentration (---). Extracellular daunorubicin concentration, 10 μM ; change of daunorubicin-containing medium supplemented with various concentrations of verapamil or using daunorubicin-containing energy-depleting medium C was performed after allowing the cells to efflux the extra accumulated daunorubicin, using medium A without verapamil. Two graphs are projected in one time axis. (d) See Fig. 3b, extracellular daunorubicin concentration, 20 μM .

Fig. 4. Initial net influx rates of daunorubicin as function of various medium concentrations of verapamil ([Vp]), using 2780^{AD} cells. (a) Experimental data, using the flow-through system (■). Conditions, see Fig. 3b. (b) Theoretical curve as calculated using Eqns 4–7 and using the parameters as described in the Results (—).

verapamil had been added (Fig. 3b). Moreover, energy depletion at constant intracellular pH resulted in a different long-term dynamic response than the effect of a verapamil concentration of 50 μM (Fig. 3c). Increasing the extracellular verapamil concentration to 375 μM after extra daunorubicin had been accumulated for 30 min caused an increase in the daunorubicin influx rate. This demonstrated the fact that, although shortly after its addition, 50 μM verapamil sufficed to block the active efflux of daunorubicin, higher concentrations of verapamil or energy-depleting medium were needed in order to block this active efflux permanently. These experiments employed extracellular daunorubicin concentrations of 10 μM (Fig. 3c).

When we used a daunorubicin concentration of 20 μM in the flowing medium, only small differences between the graphs with 30 μM and with 100 μM verapamil were observed (Fig. 3d). After 15, 25, 35 and 45 min, the differences of daunorubicin concentrations in the output were 0.52, 0.54, 0.56 and 0.52 μM , respectively.

Modelling the daunorubicin transport after addition of verapamil

Various processes require attention when verapamil is added to cells which are in steady-state with an extracellular concentration of daunorubicin. These processes include the pumping and leakage of daunorubicin before adding verapamil, which set the intracellular daunorubicin concentration, as well as the pumping and the leakage of both daunorubicin and verapamil after the latter has been added. These processes change with time as do the intracellular concentrations of daunorubicin and verapamil. In order to facilitate understanding the experiments of Figs 3 and 4, we constructed a kinetic elaboration of a simple but realistic model for these experiments. In short (for details, refer to Materials and Methods), this model contains a nonsaturable leakage of daunorubicin and verapamil across the membrane, and a pump which actively extrudes the daunorubicin and verapamil molecules from the cells. In our non-competition model (see Eqns 4 and 5), we assume that daunorubicin and verapamil are pumped independently and that verapamil functions as a non-competing inhibitor of the daunorubicin pumping. We also analyzed the implications of a competition model where daunorubicin and verapamil are presumably pumped by the same pump and will compete for this pumping.

We did not fit kinetic parameters to our experimental data. We preferred to use values for the kinetic parameters which were available in the literature or seemed to be 'best estimations', as follows.

We used a value of $0.01 \text{ nl} \cdot \text{min}^{-1} \cdot \text{cell}^{-1}$ for k , the passive permeation constant for total daunorubicin. The passive permeation coefficient for total daunorubicin was measured to be $0.01 \text{ nl} \cdot \text{min}^{-1} \cdot \text{cell}^{-1}$ for 2780^{AD} cells [23].

We used a value of $1.0 \text{ nmol} \cdot \text{min}^{-1} \cdot (10^6 \text{ cells})^{-1}$ for $V_{\text{max},X}^{\text{ow}}$, the maximal pump rate in the 2780^{AD} cells for pumping daunorubicin from the cytosol into the medium. This value could not be measured, because at an extracellular medium concentration of 50 μM , the relationship between the net accumulation rate of daunorubicin and the medium concentration did not show saturation [22]. The value we used is about twice the highest estimated maximal pump rate which we measured before [22].

For the $K_{m,X}$, the Michaelis-Menten constant for cytosolic free daunorubicin, we used a value of 1 μM . This value was estimated at $1.4 \pm 0.7 \mu\text{M}$ as described elsewhere [23].

For h , the Hill coefficient of the pump for daunorubicin molecules, we used the value of 1.5. This assumes co-operativity between two daunorubicin molecules for binding to the P-glycoprotein [35]. No data for this Hill coefficient are known for 2780^{AD} cells. The average estimated Hill coefficient for P-glycoprotein for five other human cancer cell lines, i.e. the epidermoid carcinoma cell line KB3-1 and its MDR sublines KB8 and KB8-5 and the colon carcinoma cell lines SW1116 and COLO320 was 1.5 ± 0.2 [23].

The value for the ratio of $(K_{m,D})^h/V_{\text{max},D}^{\text{iw}}$, the Michaelis-Menten constant for P-glycoprotein-mediated back flux divided by the maximal P-glycoprotein-mediated influx rate for daunorubicin, was chosen to be $10^{13} \text{ mol}^{h-1} \cdot \text{min} \cdot \text{cell} \cdot \text{l}^{-h}$. Allowing for some slippage of the pump [37], we took $V_{\text{max},X}^{\text{ow}} \cdot (K_{m,D})^h / \{V_{\text{max},D}^{\text{iw}} \cdot (K_{m,X})^h\}$ to equal 10^7 and $(K_{m,D})^h/V_{\text{max},D}^{\text{iw}}$ to equal 10^{13} .

$K_{m,D}$, the K_m for P-glycoprotein-mediated back flux of daunorubicin was assumed to be $1000 \cdot D^{h-1}$. This implies virtually no back flux of the pump from outside.

$K_{m,Y}$, the Michaelis-Menten constant for P-glycoprotein-mediated efflux of verapamil, was assumed to be 0.35 μM .

V_D and V_i , the apparent intracellular, drug-accessible volume of a cell for daunorubicin and verapamil, respectively, was taken as 430 pl for daunorubicin and 730 pl for verapamil. The apparent cellular drug-accessible distribution vol-

ume for the two drugs may be calculated from the total cellular drug amount in the steady-state for wild-type cells, divided by the used extracellular drug concentration, which should equal the cytosolic free drug concentration. In this manner, V_D was calculated to be 430 pL/cell [17] and V_i was 730 pL/cell (this study).

The passive permeation coefficient for verapamil, k' , was assumed to be $0.5 \text{ nl} \cdot \text{min}^{-1} \cdot \text{cell}^{-1}$. No conclusive experimental data on the permeation coefficient of verapamil are known. In our laboratory, we observed that the transport of verapamil is rapid at 37°C (half-life of efflux was less than 1 min; unpublished results) whereas transport of daunorubicin via passive efflux is much slower (half-life of efflux was more than 15 min) [23]. This may be explained by a lower apparent intracellular drug-accessible volume for verapamil, or a higher value of the passive permeation coefficient for verapamil, comparing verapamil and daunorubicin. Since we found an apparent intracellular drug-accessible volume of a cell which was higher for verapamil than for daunorubicin (see above), our choice of a passive permeation coefficient for verapamil which is fifty-times higher than the passive permeation coefficient for daunorubicin may be justified.

We assumed a value of $1.75 \text{ nmol} \cdot \text{min}^{-1} \cdot (10^6 \text{ cells})^{-1}$ for $V_{\text{max},Y}^{\text{ow}}$, the maximal pump rate in the 2780^{AD} cells for transporting verapamil from the cytosolic side into the medium.

The value for the ratio of $K_{m,i}/V_{\text{max},i}^{\text{iw}}$, the Michaelis-Menten constant for P-glycoprotein-mediated back inhibition divided by the maximal P-glycoprotein-mediated influx rate for verapamil, was chosen to be $2 \times 10^{12} \text{ min} \cdot \text{cell/l}$.

The $K_{m,1}$ was assumed to be 1000 μM , which implies virtually no back inhibition of P-glycoprotein by extracellular verapamil.

At $t = 0$, the verapamil medium concentration was brought from 0 to 1.

The kinetic and differential equations which were used to calculate the implications of these parameter values, are described in Materials and Methods (Eqns 4–7). We calculated the rate of the net cellular daunorubicin accumulation as a function of time after administration of verapamil. It was assumed that the extracellular daunorubicin and verapamil were present at a constant concentration throughout the experiment (due to limitations in the experimental set-up this is not strictly true, but changes in the extracellular concentration resulting from movement across the cellular plasma membranes are much smaller than the changes in intracellular concentration). Before verapamil was added, we assumed that a steady-state had been reached. Our calculations focused on the following questions, concerning the dynamic response of the extracellular daunorubicin concentration after the addition of verapamil.

(a) How should we interpret the phenomenon (Figs 3b–d) that, in the range of verapamil concentrations where immediately after verapamil has been added it completely inhibits the pump, the net influx of daunorubicin decreases with time after verapamil has been added?

(b) Why is this decrease of the net influx of daunorubicin, after verapamil has been added, slower at higher verapamil concentrations, when a concentration of 5 μM or 10 μM daunorubicin is used in the flowing medium (Figs 3b and c)?

(c) Why is the decrease with time of the net influx of daunorubicin after verapamil has been added, the same for different verapamil concentrations, when a concentration of

20 μM daunorubicin is used in the flowing medium (Fig. 3d)?

(d) Do these phenomena reflect competition by daunorubicin for the verapamil-binding-site on the pump, thereby causing a reduction of the inhibitory effects of verapamil, or do they reflect a non-competing transport of verapamil and daunorubicin?

When the pump was completely and continuously inhibited, our simulations showed that the net daunorubicin influx decreased with time after the inhibitor had been added (results not shown). However, this occurred more slowly than in simulations of inhibition by verapamil (Fig. 5a). When we increased the apparent intracellular volume by a factor of 10 (i.e. by reducing the intracellular drug concentrations), this decrease with time in the uptake rate was also considerably slower (simulation results; not shown). These simulation results suggest the following interpretation: the decrease with time of the net daunorubicin influx after verapamil was added is partly due to a decrease with time of the net leakage into the cells and partly due to the slight activity of the pump which remains and increases with time. The change with time of the two processes is caused by the increase with time of the intracellular daunorubicin concentration. The increase in its turn is caused by the net influx, which is initiated by adding verapamil. This addresses question (a).

The increase in pump flux will be proportional to the remaining activity of the pump. This leads to the phenomenon that when the pump is inhibited by 97% rather than by 99%, the net daunorubicin influx may decrease up to three times more quickly compared to that after the pump has become completely and continuously inhibited. These mechanisms which are operative in the simulation may account for the divergence of the experimental data of Fig. 3b, answering question (b) above.

When the experiment of Fig. 3b was simulated with models of non-competing (Fig. 5a) and competing (Fig. 5b) interference of verapamil with daunorubicin pumping at extracellular daunorubicin concentrations of 5 μM , the observation (Fig. 3b) that the data for the two concentrations of verapamil diverged was reaffirmed; we compared the calculated net efflux rates for the two graphs in the non-competition model (Fig. 5a) and found a difference of $1.8 \text{ pmol} \cdot \text{min}^{-1} \cdot (10^6 \text{ cells})^{-1}$ and $4.5 \text{ pmol} \cdot \text{min}^{-1} \cdot (10^6 \text{ cells})^{-1}$, at 1 min and 15 min, respectively, after verapamil had been added. For the competition model (Fig. 5b), these differences were $2.0 \text{ pmol} \cdot \text{min}^{-1} \cdot (10^6 \text{ cells})^{-1}$ and $9.7 \text{ pmol} \cdot \text{min}^{-1} \cdot (10^6 \text{ cells})^{-1}$ for 1 min and 15 min, respectively. A model with irreversible inhibition, where the inhibitor was taken immediately to equilibrate across the plasma membrane, also produced the divergence. This confirmed our assumption that the observed divergence between the two graphs in Fig. 3b does not discriminate between the competitive and non-competitive interaction of verapamil with daunorubicin.

In the above argumentation, it was supposed that the pumping rate would increase with an increase in the intracellular concentration of daunorubicin. If the pump was saturated by daunorubicin shortly after the influx had started, then the change with time of the net influx rate might not depend on the verapamil concentration (in the concentration range where verapamil virtually completely inhibits the pump). We confirmed this by simulation for the non-competition model; for K_m values of daunorubicin which were below 0.5 μM and when the extracellular daunorubicin concentration was 5 μM , the graphs for 30 μM and 100 μM verapam-

Fig. 5. Theoretical curves, calculating the net efflux rate of daunorubicin after addition of verapamil to the daunorubicin-containing perfusion medium. We used Eqns 4–7 and the parameters which have been listed in the results section. (a) The theoretical curve of the net efflux rate of daunorubicin, using the non-competition model, comparing the effects of different medium concentrations of verapamil. The concentration of daunorubicin in the perfusion medium was set to 5 μM , the concentration of verapamil was set to 30 μM (—) or 100 μM (---). Two graphs have been projected in one time axis. (b) See Fig. 5a, using the competition model. (c) See Fig. 5a, the concentration of daunorubicin in the perfusion medium was set to 20 μM . (d) See Fig. 5c, using the competition model.

amil (corresponding to Fig. 5a) did not diverge (not shown); for the chosen K_m value of 1.4 μM and when the extracellular daunorubicin concentration was 20 μM (Fig. 5c), the graphs for 30 μM and 100 μM verapamil did not diverge either. In both cases, the pump was saturated by daunorubicin. This answers question (c) above.

A competitive inhibitor effectively increases the K_m of the substrate. Therefore, if verapamil interfered competitively with the daunorubicin being pumped, saturation of the pump with daunorubicin would occur at higher daunorubicin concentrations in the medium than for the non-competitive model. Consequently, the graphs for 30 μM verapamil and 100 μM verapamil might continue to diverge at high concentrations of daunorubicin. This suggestion is confirmed by the simulation represented in Fig. 5d (confer Fig. 5c). Since it is known that the K_m of the pump for daunorubicin lies around 1.4 μM [23], these considerations and simulation results (Figs 5c and d) suggest that Fig. 3c cannot be accounted for by the model in which verapamil and daunorubicin compete. On the contrary, it can be considered to be evidence for non-competing interference of verapamil with pumping of daunorubicin. Consequently, we answer question (d) as follows: verapamil and daunorubicin are non-competing substrates for the daunorubicin pump.

DISCUSSION

The cell lines 2780^{AD} and SW-1573/1R500 have high levels of P-glycoprotein [22, 34], whereas their drug-sensitive counterparts have no detectable levels of P-glycoprotein and showed only low levels (SW-1573) or non-detectable levels (A2780) of mRNA encoding for P-glycoprotein [22, 38]. By means of a flow-through system, the present paper demonstrated increased verapamil accumulation in the parent cell lines when compared to their resistant counterparts. This MDR-specific decrease of verapamil accumulation could well result from pumping of verapamil by P-glycoprotein [3, 13, 17–20].

Sehested et al. [21] found similar accumulation of verapamil comparing wild-type EHR2 to MDR EHR2/DNR+ cells, which was energy dependent. Perhaps the rapid passive membrane transport of verapamil occluded the MDR effect on the accumulation in their studies. The high passive permeability may also have caused underestimations of verapamil accumulation in our earlier centrifugation experiments [17]. When the flow-through system was used, no wash steps were needed to determine the verapamil accumulation. Therefore, the method used in this paper may be optimal for detecting the pumping of substrates with high passive membrane permeability.

After changing to medium containing 30 μM verapamil, an almost complete inhibition of active daunorubicin efflux was obtained shortly after passage of the void volume, using P-glycoprotein containing SW1573/1R500 cells (our observations) and 2780^{AD} cells (Fig. 3b). A number of MDR cell lines has been described that lack P-glycoprotein [38–41]. Under similar measuring conditions, less than 20% of this inhibition was observed using the non-P-glycoprotein MDR cell lines SW1573/2R120 [38] and GLC4/ADR [39], even with 50–100 μM verapamil in the flowing medium. The strong effect of 30 μM verapamil shows that virtually all daunorubicin transport, measured in this study, resulted from P-glycoprotein activity.

This paper demonstrated increased accumulation of verapamil when agents known to modify the P-glycoprotein-mediated pumping of MDR-related drugs (i.e. amiodarone, bepridil, Cremophor EL or vinblastine) were added to the MDR cells. These results can be considered as further evidence that the MDR dependence of verapamil accumulation is mediated by P-glycoprotein. Most important for the interpretation that verapamil may be actively pumped was that upon removal of Cremophor EL (Fig. 2), amiodarone or vinblastine (not shown), the cells released verapamil against the concentration gradient (at this time the extracellular verapamil concentration exceeded the intracellular concentration of verapamil, as demonstrated by the influx just preceding Cremophor EL removal).

Daunorubicin did not appear to inhibit verapamil transport when we used steady-state concentrations of 0.1 μM verapamil (not shown). However, small differences in the steady-state levels of radioactivity may have been masked by the background variations of radioactivity detection. Fig. 3d did provide more substantial evidence for the non-competition model for the interference of verapamil with daunorubicin (Fig. 3d). As shown by the simulations in Figs 5a–d, in the competition model, the two lines in Fig. 3d would have diverged, in contrast with the experimental result. The results of the simulation study (Fig. 4) corresponded well with the experimental results (Fig. 4).

Our simulation studies further demonstrated that the experimental graphs, as illustrated in Figs 3 and 4, can be explained as follows. The inhibition of the pump causes an increase in the intracellular substrate concentration, which increases passive efflux and reactivates the pump for this substrate (Fig. 3). In order to inhibit P-glycoprotein effectively, one should use much higher verapamil concentrations than concentrations around the K_m for verapamil (Fig. 4), because verapamil itself is pumped and therefore the intracellular free concentration of verapamil is lower than the extracellular concentration of verapamil. Simulations without co-operativity of daunorubicin being pumped (i.e. $h = 1$), or with co-operativity between daunorubicin and verapamil being pumped, revealed only non-competition models that would match our experimental data (Figs 3 and 4; simulations not shown).

The simulations in Fig. 4 and Figs 5a–d could also be obtained in a model where verapamil functioned as an *inhibitor* rather than a substrate for pumping (simulations; not shown). Consequently, Figs 3 and 4 do not provide evidence for the contention that verapamil is pumped by MDR cells. The evidence for this pumping is shown in Figs 1 and 2. We consider it most likely that the pumping is mediated by P-glycoprotein. First, both the cell lines that pumped verapamil expressed P-glycoprotein. Second, we have no indications for the presence of non-P-glycoprotein MDR in the cell lines

used. Third, various MDR modifiers, known to inhibit P-glycoprotein-mediated pumping of various MDR-related drugs, interfered with verapamil pumping by these cells. If both verapamil and daunorubicin are pumped by P-glycoprotein, then, in the simplest model which is consistent with our experimental results, they function as non-competing substrates for that pump.

In conclusion, we found MDR-specific active verapamil transport against a concentration gradient in two drug-sensitive MDR cell line couples, i.e. A2780, 2780^{AD} and SW-1573, SW-1573/1R500, which indicates that verapamil itself is a substrate for P-glycoprotein and evidence that verapamil and daunorubicin are non-competing substrates for P-glycoprotein-mediated transport from MDR cells. This implies that the effectiveness of verapamil is not compromised by the presence of daunorubicin.

The interpretation which best matches the data presently available implies that P-glycoprotein contains two binding sites, both of which may bind daunorubicin [22, 42, 43]. Verapamil binds to the site which has the lowest affinity for daunorubicin and is then pumped. In this case, daunorubicin is not expected to interfere with the binding of verapamil to this second daunorubicin binding site (non-competition model). Consequently, only at high daunorubicin concentrations may verapamil begin to inhibit competitively.

The question whether potential MDR reversors, such as verapamil, are competing or non-competing inhibitors of P-glycoprotein and whether the P-glycoprotein substrate (the anticancer drug) is applied above or below the K_m of the pump for this substrate, is of more than academic interest. For example, we consider the case where an anticancer drug is applied such that its intracellular concentration is not far below the K_m of the P-glycoprotein. Two MDR reversors may be available, one a competing, the other a non-competing inhibitor. We apply these reversors at a concentration where they each cause 99% of the maximal influx of the drug into the MDR cell. Our results imply that this 99% inhibition may not be sufficient because some time after the addition of the reversor, the pump may have regained activity and that the non-competing inhibitor is the better choice because the increase with time in pumping of the drug by the pump will be smaller. Anticancer agents are to be preferred for which the P-glycoprotein, at the same pump activity, has a low K_m , such that saturation of the pump occurs. In that case, an increase in the dosage of the drug or addition of a non-competing inhibitor of P-glycoprotein, will be most effective.

This work was supported by the Netherlands Cancer Foundation (Grant IKA 87-16) and by the Netherlands Organization for Scientific Research (NWO).

REFERENCES

1. Moscow, J. A. & Cowan, K. H. (1988) *J. Natl Cancer Inst.* 80, 14–20.
2. Deuchars, K. L. & Ling, V. (1989) *Semin. Oncol.* 16, 156–165.
3. Cano-Gauchi, D. F. & Riordan, J. R. (1987) *Biochem. Pharmacol.* 36, 2115–2123.
4. Tsuruo, T., Iida, H., Tsukagoshi, S. & Sakurai, Y. (1981) *Cancer Res.* 41, 1967–1972.
5. Bradley, G., Juranka, P. F. & Ling, V. (1988) *Biochim. Biophys. Acta* 948, 87–128.
6. Beck, W. T. (1990) *Eur. J. Cancer* 26, 513–515.
7. Tsuruo, T., Iida, H., Tsukagoshi, S. & Sakurai, Y. (1982) *Cancer Res.* 42, 4730–4733.

8. Tsuruo, T., Iida, H., Tsukagoshi, S. & Sakurai, Y. (1983) *Cancer Res.* 43, 2267–2272.
9. Dalton, W. S., Grogan, T. M., Meltzer, P. S., Scheper, R. J., Durie, B. G. M., Taylor, C. W., Miller, T. P. & Salmon, S. E. (1989) *J. Clin. Oncol.* 7, 415–424.
10. Ford, J. M. & Hait, W. N. (1990) *Pharmacol. Rev.* 42, 155–199.
11. Safa, A. R., Glover, C. J., Meyers, M. B., Biedler, J. L. & Felsted, R. L. (1986) *J. Biol. Chem.* 261, 6137–6139.
12. Cornwell, M. M., Safa, A. R., Felsted, R. L., Gottesman, M. M. & Pastan, I. (1986) *Proc. Natl Acad. Sci. USA* 83, 3847–3850.
13. Yusa, K. & Tsuruo, T. (1989) *Cancer Res.* 49, 5002–5006.
14. Friche, E., Jensen, P. P., Sehested, M., Demant, E. J. F. & Nissen, N. I. (1990) *Cancer Commun.* 2, 297–303.
15. Broxterman, H. J. & Pinedo, H. M. (1991) *J. Cell Pharmacol.* 2, 239–247.
16. Safa, A. R. (1988) *Proc. Natl Acad. Sci. USA* 85, 7187–7191.
17. Broxterman, H. J., Pinedo, H. M., Kuiper, C. M., Kaptein, L. C. M., Schuurhuis, G. J. & Lankelma, J. (1988) *FASEB J.* 2, 2278–2282.
18. Yang, C.-P. H., Cohen, D., Greenberger, L. M., Hsu, S. I.-H. & Horwitz, S. B. (1990) *J. Biol. Chem.* 265, 10282–10288.
19. Horio, M., Chin, K.-V., Currier, S. J., Goldenberg, S., Williams, C., Pastan, I., Gottesman, M. M. & Handler, J. (1989) *J. Biol. Chem.* 264, 14880–14884.
20. Warr, J. R., Anderson, M. & Ferguson, J. (1988) *Cancer Res.* 48, 4477–4483.
21. Sehested, M., Skovsgaard, T., Jensen, P. B., Friche, E. & Bindlev, N. (1990) *Br. J. Cancer* 62, 37–41.
22. Spoelstra, E. C., Dekker, H., Schuurhuis, G. J., Broxterman, H. J. & Lankelma, J. (1991) *Biochem. Pharmacol.* 41, 349–359.
23. Spoelstra, E. C., Westerhoff, H. V., Dekker, H. & Lankelma, J. (1992) *Eur. J. Biochem.* 207, 567–579.
24. Lankelma, J., Spoelstra, E. C., Dekker, H. & Broxterman, H. J. (1990) *Biochim. Biophys. Acta* 1055, 217–222.
25. Schuurhuis, G. J., Broxterman, H. J., Pinedo, H. M., van Heijningen, T. H. M., van Kalken, C. K., Vermorken, J. B., Spoelstra, E. C. & Lankelma, J. (1990) *Br. J. Cancer* 62, 591–594.
26. Van der Graaf, W. T. A., de Vries, E. G. E., Uges, D. R. A., Nanninga, A. G., Meijer, C., Vellenga, E., Mulder, P. O. M. & Mulder, N. H. (1991) *Int. J. Cancer* 48, 616–622.
27. Woodcock, D. M., Jefferson, S., Linsenmeyer, M. E., Crowther, P. J., Chojnowski, G. M., Williams, B. & Bertoncello, I. (1990) *Cancer Res.* 50, 4199–4203.
28. Schuurhuis, G. J., Broxterman, H. J., van der Hoeven, J. J. M., Pinedo, H. M. & Lankelma, J. (1987) *Cancer Chemother. Pharmacol.* 20, 285–290.
29. Keizer, H. G., Schuurhuis, G. J., Broxterman, H. J., Lankelma, J., Schoonen W. G. E. J., van Rijn, J., Pinedo, H. M. & Joenje, H. (1989) *Cancer Res.* 49, 2988–2993.
30. Rogan, A. M., Hamilton, T. C., Young, R. C., Klecker, R. W. & Ozols, R. F. (1984) *Science* 224, 994–996.
31. Broxterman, H. J., Pinedo, H. M., Kuiper, C. M., van der Hoeven, J. J. M., de Lange, P., Quak, J. J., Scheper, R. J., Keizer, H. G., Schuurhuis, G. J. & Lankelma, J. (1989) *Int. J. Cancer* 43, 340–343.
32. Lankelma, J., Laurensse, E. & Pinedo, H. M. (1982) *Anal. Biochem.* 127, 340–345.
33. Lehninger, A. L. (1975) *Biochemistry*, 2d edn, pp. 197–201, Worth Publishers, New York.
34. Skovsgaard, T. (1977) *Biochem. Pharmacol.* 27, 1221–1227.
35. Hill, T. L. (1985) *Cooperativity theory in biochemistry*, pp. 63–67, Springer, Berlin.
36. Van der Meer, R., Akerboom, T. P. M., Groen, A. K. & Tager, J. M. (1978) *Eur. J. Biochem.* 84, 413–420.
37. Westerhoff, H. V. & van Dam, K. (1987) *Thermodynamics and control of biological free-energy transduction*, pp. 246–249, Elsevier, Amsterdam.
38. Kuiper, C. M., Broxterman, H. J., Baas, F., Schuurhuis, G. J., Haisma, H. J., Scheffer, G. L., Lankelma, J. & Pinedo, H. M. (1990) *J. Cell Pharmacol.* 1, 35–41.
39. Zijlstra, J. G., de Vries, E. G. E. & Mulder, N. H. (1987) *Cancer Res.* 47, 1780–1784.
40. McGrath, T., Latoud, C., Arnold, S. T., Safa, A. R., Felsted, R. L. & Center, M. S. (1989) *Biochem. Pharmacol.* 38, 3611–3619.
41. Slovak, M. L., Coccia, M., Meltzer, P. S. & Trent, J. M. (1991) *Anticancer Res.* 11, 423–428.
42. Bruggemann, E. P., Germann, U. A., Gottesmann, M. M. & Pastan, I. (1989) *J. Biol. Chem.* 264, 15483–15488.
43. Greenberger, L. M., Lisanti, C. J., Silva, J. T. & Horwitz, S. B. (1991) *J. Biol. Chem.* 266, 20744–20751.