The Penetration of Anticancer Drugs through Tumor Tissue as a Function of Cellular Adhesion and Packing Density of Tumor Cells

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Abstract

To reach cancer cells in optimal quantities, therapeutic agents must be delivered to tumors through their imperfect blood vascular system, cross vessel walls into the interstitium, and penetrate multiple layers of tissue. Strategies to enhance drug penetration have potential to improve therapeutic outcome. The development of multicellular layers (MCLs), in which tumor cells are grown on a semipermeable Teflon support membrane, has facilitated quantification of drug penetration through solid tissue. The goals of the present study were to quantify the penetration of anticancer drugs as a function of cellular adhesion and packing density and to determine the effects of variable penetration on therapeutic efficacy. We therefore compared the properties of MCLs grown from two epithelioid and round subclones of a colon carcinoma cell line. One pair of epithelioid and round sublines differed in expression of α-E-catenin, and both pairs generated MCLs with different packing density. The penetration of commonly used anticancer agents (paclitaxel, doxorubicin, methotrexate, and 5-fluorouracil) through MCLs derived from these cell lines was significantly greater through the round (loosely packed) than through the epithelioid (tightly packed) sublines. In MCLs treated with doxorubicin, we observed greater survival in the tightly packed cell lines than in the loosely packed cell lines. Impaired penetration of anticancer agents through MCLs derived from the tightly packed cell lines and relative resistance to killing of cells within them by doxorubicin treatment strengthen the role of tumor cell adhesion and packing density as contributing to drug resistance. (Cancer Res 2006; 66(2): 1033-9)

Introduction

The causes of drug resistance in solid tumors are multifactorial and most research has concentrated on genetic and cellular factors, which contribute to resistance of the individual cells. The proposed mechanisms of drug resistance in cancer are based largely on the study of drug-resistant variants isolated from tumor cells exposed to various classes of drugs in monolayer tissue culture. However, these methods of analysis tend to put little or no emphasis on physiologic mechanisms of drug resistance operative at the level of the whole tissue (1–4). To reach cancer cells in optimal quantities, a therapeutic agent must be delivered to a tumor through its imperfect blood vasculature, cross vessel walls into the interstitium, and penetrate multiple layers of solid tissue. This requirement may present a barrier to effective treatment and may be as important a cause of drug resistance as genetic and cellular factors (1–4).

Early studies of drug penetration through tissue employed multicellular spheroids, which provide a reasonable model for solid tumors with similarities of cellular environment including generation of an extracellular matrix and gradients of cell proliferation and nutrient concentration, gene expression, and biological behavior of cells (5–9). Studies using fluorescent or radiolabeled drugs have shown poor penetration of doxorubicin, vinblastine, paclitaxel, and methotrexate into the deeper layers of spheroids. Nevertheless, it is difficult to quantify drug penetration using the spheroid model.

An alternative model, the multicellular layer (MCL) model, developed by Wilson and his colleagues, provides a quantitative method that permits direct assessment of drug penetration through solid tissue (10, 11). Tumor cells are grown on collagen-coated microporous Teflon membranes. The resulting MCLs have a symmetrical, planar structure with tumorlike physiology. To examine penetration, a drug is added on one side of the MCL and its appearance on the other side of the MCL is measured as a function of time by appropriate analytic methods (Fig. 1). Like spheroids, MCLs share several properties with solid tumors derived from the same cell type, including a similar but not identical extracellular matrix and tight junctions between epithelial cells (12). Studies conducted in our laboratory and others have shown poor penetration of many commonly used anticancer drugs through MCLs generated from several human and murine cell lines (11–17). Drug penetration through MCLs was shown to be improved by agents that inhibit cellular uptake of anticancer drugs, suggesting that the penetration of chemotherapeutic agents is largely mediated by diffusion through the extracellular matrix (18, 19).

Previous studies using solid tumor histocultures and xenografts have shown poor drug penetration into solid tumors with high packing density (20), and drug penetration was shown to improve on administration of agents that induced apoptosis and reduction in cell density (20–22). The goals of the present study were to use the MCL model to quantify the penetration of anticancer drugs as a function of packing density of the cells and to determine the effect of drug penetration on therapeutic efficacy. We therefore compared the properties of MCLs grown from two different epithelioid clones of HCT-8 colon carcinoma cells and round subclones derived from each of them. The epithelioid and round sublines have different cell adhesion properties and generate MCLs with different packing density.

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Materials and Methods

Cell lines. The HCT-8 cell lines consisted of epithelioid sublines and round variants that have been reported to possess a frame-shift mutation in the DNA repair gene HMMH6 and heterozygosity for CTNNNA1 which codes for α-E-catenin (25). Due to this deficiency, round cells are unable to form adherens junctions and they generate MCLs with a large extracellular space whereas the parental epithelioid clones form tightly packed MCLs. The HCT-8 Ea and Ra sublines, referred to below as Ea and Ra sublines, were kindly provided by Dr. W.R. Wilson (Auckland Cancer Society Research Centre, University of Auckland, Auckland, New Zealand). These cells were grown as monolayers in α-MEM (Life Technologies, Inc., Burlington, ON, Canada) supplemented with 10% fetal bovine serum (FBS; Hyclone, Logan, UT) at 37° in a humidified atmosphere of 95% air plus 5% CO2. The HCT-8/E11 and HCT-8/IR1 cell lines, referred to below as E11 and IR1 sublines, were generously provided by Dr. M. Bracke (Ghent University Hospital, Gent, Belgium). These cells were grown as monolayers in RPMI medium (Life Technologies) containing 1 mmol/L pyruvate supplemented with 10% FBS. Cells were reestablished from frozen stock every 4 months and assessed periodically for the presence of Mycoplasma.

Growth and characterization of MCLs. Exponentially growing cells (∼5 × 105) were seeded on collagen-coated, semipermeable Teflon membrane culture inserts (Millipore, Bedford, MA). Briefly, 150 μL of collagen type III were dissolved in 0.01 mol/L HCl and diluted in a 1:4 ratio with 60% ethanol to a final concentration of 0.75 mmol/L. This was applied to the culture inserts and allowed to dry overnight. Cells were allowed to attach for 4 hours and the membranes were then submerged in a large volume of stirred α-MEM or RPMI medium containing 1 mmol/L pyruvate, supplemented with 10% FBS, and allowed to grow for 5 days. Uniformity of MCL growth was assessed using a light microscope; only MCLs with uniform growth across the membrane were used in experiments. To determine the number of cells in MCLs, one or more of them were selected at random, trypsinized, and the cells counted using a Coulter counter.

To characterize MCLs, they were fixed in 10% neutral buffered formalin for 24 hours and then processed through graded concentrations of ethanol (70%, 95%, and 100%). They were placed in xylene overnight and then embedded in paraffin and cut into 4-μm-thick sections. They were stained with H&E or Masson’s trichrome to stain for extracellular matrix or with 4,6-diamidino-2-phenylindole (DAPI) to quantify cellular packing density. DAPI-stained MCL sections were viewed with a Zeiss Axiosvert 200M and packing density was quantified as the number of nuclei per unit surface area using Media Cybernetics Image Pro PLUS software.

Immunohistochemical staining for evaluation of matrix proteins was undertaken using a rabbit antilaminin polyclonal antibody (Sigma Chemical Co., St. Louis, MO) and human monoclonal antibodies against collagen type IV (DAKO Corp., Carpinteria, CA), fibronectin, E-cadherin, and β-catenin (all from BD Transduction Laboratories, Lexington, KY). Briefly, tissue sections were dewaxed in xylene and rehydrated through graded ethanol to water. Endogenous peroxidase activity was blocked with 3% aqueous hydrogen peroxide solution. Antigen retrieval was undertaken by pepsin digestion or heat retrieval. The slides were then incubated with the primary antibody for 1 hour at room temperature. Samples were washed in PBS and incubated for 30 minutes with either biotin antirabbit (Vector Laboratories, Burlingame, CA) or antimouse immunoglobulin G (IgG; Signet Pathology Systems, Inc., Dedham, MA) followed by 30-minute incubation with streptavidin-horseradish peroxidase complex (Signet Laboratories). Finally, the slides were counterstained lightly with Mayer’s hematoxylin, dehydrated through alcohol, and mounted in Permount.

Western blotting for α-E-catenin. For Western blotting, MCLs were washed twice with ice-cold PBS and incubated with 500 μL of lysis buffer [50 mmol/L HEPES (pH 8.0), 10% glycerol, 1% Triton X-100, 150 mmol/L NaCl, 1 mmol/L EDTA, 1.5 mmol/L MgCl2, 100 mmol/L NaF, 10 mmol Na3PO4, 1 mmol/L Na2VO4, and 1 tablet/7 mL protease inhibitor cocktail from Roche Diagnostics (Mannheim, Germany)] for 1 hour in 4°C. Lysates were cleared from the insoluble material and the resulting extracts were assayed for total protein content using a BCA Protein Assay Kit (Pierce, Rockford, IL). Equivalent quantities of protein were separated using 10% SDS-PAGE gels and subsequently transferred onto polyvinylidene difluoride membranes. Membrane blots were blocked overnight with TBS-Tween 20 containing 5% milk at 4°C. Membranes were probed at room temperature for 1 hour with rabbit polyclonal antibody against human α-E-catenin antibody (Sigma-Aldrich, St. Louis, MO). Blots were then incubated with horseradish peroxidase–linked antirabbit antibody (Amersham Biosciences, Baie d’Urfé, Quebec, Canada) for 1 hour at room temperature. Proteins were detected using enhanced chemiluminescence per instructions of the manufacturer (Amersham Biosciences). Blotting

Figure 1. A, the experimental chamber used to assess drug penetration through a MCL. Anticancer agents dissolved in 1% agar (to prevent convection) are added to compartment 1 and the insert containing the drug and MCL is then floated in media. Samples are obtained from compartment 2 through the sampling port while the gas port delivers a mixture of 95% air and 5% CO2. B, the dual chamber model avoids the use of agar and facilitates the disaggregation of cells in a MCL. In this system, drug at selected concentrations was dissolved in a MCL. Anticancer agents dissolved in 1% agar (to prevent convection) are applied to the culture inserts and allowed to dry overnight. Cells were allowed to attach for 4 hours and the membranes were then submerged in a large volume of stirred α-MEM or RPMI medium containing 1 mmol/L pyruvate, supplemented with 10% FBS, and allowed to grow for 5 days. Uniformity of MCL growth was assessed using a light microscope; only MCLs with uniform growth across the membrane were used in experiments. To determine the number of cells in MCLs, one or more of them were selected at random, trypsinized, and the cells counted using a Coulter counter.

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The mixture was denatured at 65°C, 75 mmol/L KCl, and 3 mmol/L MgCl₂ and dTT, in addition to 4 mmol/L Mg²⁺, 400 nmol/L dNTPs, 400 nmol/L of primers, and 50°C. Reverse transcription was conducted using DNase-treated total RNA mixed with anchored oligo-dT primer, 3°C RCPA (5′AAGCAGGTGTGATACCCGAGATGC-(dT)₃-3′), and deoxyribonucleotide triphosphates (dNTP; each of dATP, dCTP, dTTP, and dGTP at pH 7.0). The mixture was denatured at 65°C for 5 minutes and immediately put on ice. Reverse transcription was done at 42°C for 2 hours in First-Strand Buffer [50 mmol/L Tris-HCl (pH 8.3) at room temperature, 75 mmol/L KCl, and 3 mmol/L MgCl₂] and dTT, in addition to 40 units of RNaseOUT and 250 units of SuperScript II RT (Invitrogen, Burlington, Ontario, Canada). PCR to detect α-catenin was conducted using the following primers as previously described by Oda et al. (24): primer S1, α-E-catenin-5′-CTTCCGGGGCTCTGGATTTA-3′ and primer A3, α-E-catenin-5′-CACTGTTCGGCAATCTCCG-3′ (Invitrogen). The S1-A3 primer set was used for amplification of α-E-catenin cDNA between exons 1 and 3 as previously published by Oda et al. (24). PCR using S1 and A3 will produce a ~2,000-bp product. Glyceraldehyde-3-phosphate dehydrogenase (GAPDH) primers were used as controls for cDNA quality and RNA extracted from each cell line was used as a negative control. All PCR reactions were conducted using the following conditions: one cycle at 94°C for 3 minutes and 40 cycles at 94°C for 15 seconds, 53°C for 30 seconds, and 72°C for 30 seconds using a Platinum Taq Polymerase (Invitrogen) and a Platinum Taq DNA polymerase PCR buffer (Invitrogen) with 4 mmol/L Mg²⁺, 400 mmol/L dNTPs, 400 nmol/L of primers, and 50 mmol/L probe in a total volume of 25 μL.

Anticancer drugs. [³H]Paclitaxel (specific activity, 5 μCi/mmol/L) and [³H]-5-fluorouracil (5-FU; specific activity, 10 μCi/mmol/L) were purchased from Maveerik Biochemicals, Inc. (Brea, MA). [¹⁴C]Doxorubicin (specific activity, 25 μCi/mmol/L) and [¹⁴C]methotrexate (specific activity, 250 μCi/mmol/L) were purchased from Amersham Pharmacia Biotech (Amersham, United Kingdom) and [¹⁴C]Sucrose (specific activity, 50 μCi/mmol/L) was obtained from Perkin-Elmer Life Sciences, Inc. (Boston, MA). Unlabeled doxorubicin (Pharmacia, Mississauga, Ontario, Canada), paclitaxel (Bristol-Myers Squibb, Montreal, Quebec, Canada), 5-FU, and methotrexate (both from Mayne Pharma, Montreal, Quebec, Canada) were obtained in their clinical formulations.

Penetration of anticancer drugs. Solutions containing radiolabeled anticancer drugs were prepared in 2% α-MEM (without FBS) and mixed in a 1:1 ratio with 1% agar solution. A volume of 0.5 mL of this mixture was added to one side of the MCL (compartment 1, Fig. 1A); the 1% agar solution was included to prevent convection. MCLs were then floated on 18 mL of stirred culture media (compartment 2, Fig. 1A). A cell-free tissue culture insert was included in all experiments as a control. Experiments were conducted at 37°C in glass vials exposed to 95% air/5% CO₂. The appearance of drugs in compartment 2 as a function of time was assessed by liquid scintillation counting of 150 μL samples withdrawn from compartment 2. Drug penetration through MCLs is presented as a ratio of C/C∞, where C is the measured drug concentration and C∞ represents the calculated concentration of the drug when it has equilibrated between the two compartments. [¹¹C]Sucrose was included as an internal standard at a concentration of 3 μmol/L in all experiments, except those conducted with [¹⁴C]doxorubicin; only MCLs with a maximum variation of ±20% in sucrose penetration were used for analysis. To minimize statistical variation, experiments conducted with [¹⁴C]doxorubicin were repeated four times and only MCLs with total cell numbers ranging from 3 × 10⁶ to 4.5 × 10⁶ were used to assess doxorubicin penetration.

The initial concentration of drugs in compartment 1 was as follows: 25 μmol/L paclitaxel, 5 μmol/L doxorubicin, 10 μmol/L methotrexate, and 77 μmol/L 5-FU. These concentrations approximate those that can be achieved in serum after in vivo administration and permit sensitive detection of the drug in compartment 2; they were achieved using a mixture of radiolabeled and unlabeled drugs.

Fluorescent micrographs of drug penetration were obtained by treating MCLs derived from each subline with 10 μmol/L using a dual chamber reservoir apparatus (Fig. 1B). MCLs were then fixed in 10% neutral buffered formalin and processed as previously described under low light conditions. Images were obtained using Zeiss Axiovert 200M with Roper Scientific Coolsnap HQ.

Clonogenic assays. The sensitivity of each cell line to methotrexate, doxorubicin, 5-FU, and paclitaxel was assessed in a clonogenic assay. Exponentially growing cells were exposed for 24 hours to various doses of chemotherapeutic agents in monolayer. Cells were then trypsinized, washed twice, and serial dilutions were plated in six-well plates with each well containing 5 mL of media. The sublines showed sensitivity only to doxorubicin and this drug was selected for further experiments.

MCLs containing 3 × 10⁶ to 5 × 10⁶ cells were exposed at 37°C to varying concentrations of doxorubicin for 24 hours in a dual reservoir apparatus in which drugs were added to stirred media on one side of the MCL (Fig. 1B). The dual chamber apparatus was used instead of the vertical chamber to avoid the use of agar and thereby to facilitate disaggregation and subsequent plating of cells. After treatment, MCLs were disaggregated by pipetting, trypsinized, and washed twice. Serial dilutions were plated as described above. Plates were incubated for 10 days (Ra and R11 cells) or 14 days (Ea and E11 cells) at 37°C in 95% air/5% CO₂ and 90% humidity. Cells were then stained with methylene blue and colonies containing >50 cells were counted.

Cell cycle distribution. MCLs were disaggregated by pipetting, trypsinized, washed twice, and resuspended in PBS at 1 × 10⁶ cells/mL. Cells from MCLs and single-cell suspensions were incubated with 1 μmol/L propidium iodide containing 0.1% Triton X-100 (Pierce) and 50 mg/mL RNase (Qiagen, Inc., Mississauga, Ontario, Canada) for 30 minutes. Multicycle AV software version 2.5 (Phoenix Flow Systems, San Diego, CA) was used for cell cycle analysis.

Statistical analysis. Data for drug penetration and for cell survival are presented as mean ± SE for at least three replicate experiments.

### Table 1. Characterization of MCLs derived from HCT-8 cell lines

<table>
<thead>
<tr>
<th>MCL</th>
<th>Doubling time (h)</th>
<th>MCL thickness (layer with 3 × 10⁶-5 × 10⁶ cells), μm</th>
<th>Packing density (percentage of nuclear area ± SD)</th>
<th>Histologic morphology</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCT-8EA</td>
<td>42</td>
<td>150</td>
<td>54.4 ± 4.6</td>
<td>Tightly packed; epithelioid morphology; fingerlike projections on MCL surface</td>
</tr>
<tr>
<td>HCT-8EII</td>
<td>48</td>
<td>200</td>
<td>50 ± 4.9</td>
<td></td>
</tr>
<tr>
<td>HCT-8Ra</td>
<td>28</td>
<td>175</td>
<td>32.3 ± 3.8</td>
<td>Loosely packed; round morphology</td>
</tr>
<tr>
<td>HCT-8IR1</td>
<td>30</td>
<td>230</td>
<td>39.3 ± 3.8</td>
<td></td>
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</table>

with α-tubulin [monoclonal mouse IgG from Oncogene (San Diego, CA) and horseradish peroxidase-linked mouse IgG from Amersham Biosciences (Buckinghamshire, United Kingdom)] was used to control for protein and horseradish peroxidase–linked mouse IgG from Amersham Biosciences (Buckinghamshire, United Kingdom) was used to control for protein.
Comparisons between data for HCT-8/R and HCT-8/E cell lines were analyzed using SigmaPlot software. Statistical significance was based on two-sided t tests with $P_s < 0.05$.

**Results**

**Characterization of cell lines and MCLs.** Properties of the cell lines are summarized in Table 1. Cells within MCLs derived from the Ea and E11 cells displayed epithelial morphology with close contact between cells and the formation of fingerlike projections on the surface of the MCLs (Fig. 2A and C). In contrast, Ra and 1R1 cells formed loosely packed MCLs with significantly lower cell concentration than those derived from the corresponding Ea and E11 cells (Fig. 2B and D).

Immunohistochemical assessment of the extracellular matrix of MCLs derived from the sublines indicated the presence of laminin in all cell lines but no staining for collagen IV or fibronectin. Although laminin distribution was observed throughout the MCLs, its deposition was particularly evident on the MCL surface and especially along the fingerlike projections of the MCLs formed from the E11 and Ea sublines.

Western blot analysis showed no $\alpha$-E-catenin expression in the 1R1 subline, but surprisingly, expression was similar in both Ea and Ra sublines (Fig. 3A). Using reverse transcription-PCR (RT-PCR) analysis with the S1 and A3 primer set, $\alpha$-E-catenin mRNA splicing in the Ra subline between exons 1 to 13 was similar to that in the Ea subline (Fig. 3B). Immunohistochemical analysis showed expression of E-cadherin and $\beta$-catenin in all sublines (data not shown).

**Drug penetration through MCLs.** The penetration of all anticancer drugs tested was slower through the MCLs than through the cell-free Teflon membrane (Fig. 4; Table 2); their penetration was also greater through MCLs derived from the loosely packed Ra and 1R1 sublines than through MCLs derived from the corresponding tightly packed Ea or E11 sublines.

Fluorescent micrographs of doxorubicin penetration through MCLs derived from Ea and E11 sublines show that, at 15 minutes, penetration is limited to the peripheral cell layers whereas, at 6 hours, doxorubicin penetration involves $\sim 1/3$ of the MCL (Fig. 5). In MCLs derived from the Ra and R1 sublines, drug penetration is initially restricted to the outer cell layers (those adjacent to the drug-containing chamber) whereas, at 6 hours posttreatment, doxorubicin fluorescence is prominent in all cell layers and the outer cell layers have begun to dissociate from the MCL. At 24 hours posttreatment, the outer cell layers dissociate from the MCL; this disaggregation was especially prominent in the MCLs derived from the R1 subline (Fig. 5).

**Sensitivity to doxorubicin.** Survival curves for cells in monolayer and for cells in the corresponding MCLs treated with doxorubicin for E11 and 1R1 sublines are shown in Fig. 6. Cells in monolayer are more sensitive than cells in MCLs with no significant difference in sensitivity between the sublines in monolayer. Cells in the more loosely packed MCLs derived from the Ra and 1R1 cell lines were considerably more sensitive than those in MCLs derived from the corresponding tightly packed Ea and E11 cell lines ($P = 0.014$ for Ea and Ra and $P = 0.048$ for E11 and 1R1).

Flow cytometric DNA analysis showed that $\sim 14.2 \pm 1.2%$ and $16.9 \pm 2.9%$ of MCLs derived from E11 and 1R1 cells, respectively, were in the S phase. Hence, variations in cytotoxicity between the two cell lines were not likely to be due to differences in the percentage of S-phase cells between MCLs derived from these cells.
Discussion

The present study illustrates that the packing density and adhesive properties of cells may influence drug penetration and toxicity in solid tumors. Using two sets of colon carcinoma cell lines and commonly used antineoplastic agents, we have shown an inverse correlation between tumor packing density and drug penetration. Penetration of radiolabeled drugs across the MCLs was assessed by quantifying the concentration of radiolabel in the receiving compartment; we recognize that radiolabel might be associated with a metabolite; thus, this provides an upper limit for the rate of penetration of the parent compound through the MCLs.

Visualization of doxorubicin penetration through MCLs established from E11 and R1 sublines shows that, initially, drug penetration is limited to the periphery of the MCLs (adjacent to the drug-containing chamber). Although the penetration of doxorubicin increases over the course of 24 hours, the level of drug penetration is greater through the loosely packed than through the tightly packed MCLs. These observations are further supported by the differences in cytotoxicity that were observed after 24 hours of treatment with doxorubicin: higher levels of survival in the tightly packed MCLs derived from Ea colon cancer and HCT-8E11 cells. The disaggregation of proximal layers of MCLs derived from 1R1 and Ra sublines (Fig. 5, bottom right) after treatment with doxorubicin might facilitate further penetration of the drug into the deeper layers of the MCLs. Our data support the role of tumor microenvironment in limiting drug penetration and thereby in causing effective drug resistance.

The cell lines used in this study consisted of two tightly packed and two loosely packed cell lines. Quantification of packing density and characterization of the tightly and loosely packed sublines did not reveal morphologic differences between Ea and Ra sublines. Because Ea and Ra sublines were obtained as HCT-8 sublines and previous studies have shown that the transition from the epithelioid to the round morphotype is due to a mutation in the second allele of α-E-catenin, the expression of α-E-catenin in the Ra subline was unexpected (23, 25). Our experiments to characterize the adhesion defect in the Ra subline did not reveal differences in the expression of E-cadherin or other extracellular matrix proteins.
components. Although the nature of the molecular mechanisms leading to the transition from Ea to Ra has not been elucidated, the morphologic differences (including packing density and response to chemotherapeutic agents) observed between the Ea and Ra sublines were similar to those found in the E11 and 1R1 sublines.

The majority of in vitro studies of drug resistance focus on mechanisms that operate at the level of the single cell. Assessment of cellular behavior in monolayer cultures in vitro has contributed to the understanding of the role of DNA repair/apoptotic pathways, drug target alterations, and multidrug resistance mediated by drug efflux pumps in drug resistance (4, 26, 27). However, monolayer systems disregard the contribution of tumor physiology, particularly cell-cell interactions, the extracellular matrix, and tumor microenvironment, to chemotherapeutic resistance. Both Ea and E11 sublines show slightly greater sensitivity to doxorubicin than Ra and 1R1 sublines when treated in monolayer. Our data also show greater cell killing in monolayer than in multilayers for all concentrations tested and, in contrast to monolayers, better cell killing in the loosely packed MCLs derived from Ra and 1R1 cells than the corresponding tightly packed MCLs. Whereas drug consumption in the MCLs might have some effect on their effective drug exposure as a function of time, this is likely to be small, and will apply to MCLs derived from each of the sublines. Our findings are in agreement with other studies that have shown that some types of drug resistance are expressed only in three-dimensional tissue; they provide evidence for the role of tumor architecture, particularly packing density, in drug resistance of solid tumors.

Strategies that modify or alter solid tumor physiology have been shown to improve the cytotoxicity of several antineoplastic agents. Studies conducted by St. Croix et al. (28) have shown that treatment with hyaluronidase increases the susceptibility of spheroids derived from EMT-6 mammary carcinoma cells to treatment with 4-hydroxycyclophosphamide as compared with untreated spheroids. The authors conclude that hyaluronidase acts as an antiadhesive agent that leads to spheroid disaggregation and increased chemosensitivity. These experiments suggest that specific interactions between cancer cells and their environment (cell-cell as well as cell-matrix adhesion) ultimately contribute to the outcome of chemotherapy. Sherman-Baust et al. (29) have shown up-regulation of collagen VI in cisplatin-resistant ovarian cancer spheroids whereas studies by Netti et al. (30) have shown that tumors with a well-defined collagen network are more resistant to penetration of macromolecules (such as IgG) compared with tumors that exhibit a loose collagen network. Collagenase treatment of the tumors, leading to the degradation of collagen, was shown to enhance the diffusion coefficient of index molecules through these tumors, providing further evidence for the role of tumor microenvironment as a barrier to drug penetration. In addition, modification

<table>
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<th>Cell line</th>
<th>Doxorubicin</th>
<th>5-Fluorouracil</th>
<th>Paclitaxel</th>
<th>Methotrexate</th>
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<tr>
<td>Ea</td>
<td>12.3 ± 1.0</td>
<td>12.1 ± 0.6</td>
<td>18.8 ± 2.1</td>
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<td>14.8 ± 3.9</td>
<td>45.4 ± 4.6</td>
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<tr>
<td>Ra</td>
<td>55.1 ± 3.2</td>
<td>32.3 ± 7.1</td>
<td>46.9 ± 1.9</td>
<td>33.2 ± 3.0</td>
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<tr>
<td>1R1</td>
<td>35.8 ± 4.5</td>
<td>46.9 ± 1.9</td>
<td>58.4 ± 1.6</td>
<td>45.1 ± 8.0</td>
</tr>
<tr>
<td>Cell-free</td>
<td>84.1 ± 5.4</td>
<td>80.3 ± 8.5</td>
<td>58.4 ± 1.6</td>
<td>45.1 ± 8.0</td>
</tr>
</tbody>
</table>

NOTE: Percent drug penetration is obtained from the ratio of the drug concentration in compartment 2 (at 6 hours) to drug concentration at equilibrium ± SD. Data represent results from three to five experiments. Penetration of paclitaxel and methotrexate was not studied in MCLs derived from E11 and 1R1 cell lines.

Figure 5. Penetration of doxorubicin through MCLs derived from E11 and 1R1 sublines after 6 and 24 hours. Doxorubicin penetration is slower through MCLs derived from the tightly packed E11 cell line with distribution of the drug largely in the proximal layers. Similar patterns were observed using Ea and Ra sublines although, at 24 hours posttreatment, less MCL disaggregation was observed for these cell lines than for the E11 and 1R1 subtypes.
Drug Penetration and Packing Density

Figure 6. Clonogenic assays conducted using HCT-8E11 and HCT-81R1 cells exposed to varying concentrations of doxorubicin in monolayers or MCLs for 24 hours. Cell survival is presented as the ratio of colonies at a particular drug concentration to colonies in the untreated condition. Points, mean from three experiments; bars, SD. Similar results were obtained using Ea and Ra sublines (data not shown).

References


of tumor packing density using pretreatment schedules with doxorubicin or paclitaxel for 24 hours reduced cell density and improved the distribution of highly protein-bound drugs in solid tumors (21, 22).

In conclusion, our findings support the role of the tumor microenvironment in drug resistance in solid tumors. We have shown that tumor packing density poses a barrier to effective drug penetration, which will in turn decrease chemotherapeutic cytotoxicity. Future studies will focus on modifying cell packing density to improve the penetration of index drugs and hence drug activity.

Acknowledgments


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The Penetration of Anticancer Drugs through Tumor Tissue as a Function of Cellular Adhesion and Packing Density of Tumor Cells

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