Renal human organic anion transporter 3 increases the susceptibility of lymphoma cells to bendamustine uptake

Yohannes Hagos,1 Philip Hundertmark,1 Volodymyr Shnitsar,1 Venkata V. V. R. Marada,1 Gerald Wulf,2 and Gerhard Burckhardt1

1Institut für Vegetative Physiologie und Pathophysiologie, Universitätsmedizin Göttingen, Göttingen, Germany; and 2Klinik für Hämatologie und Onkologie, Universitätsmedizin Göttingen, Göttingen, Germany

Submitted 20 August 2014; accepted in final form 2 December 2014

Hagos Y, Hundertmark P, Shnitsar V, Marada VV, Wulf G, Burckhardt G. Renal human organic anion transporter 3 increases the susceptibility of lymphoma cells to bendamustine uptake. Am J Physiol Renal Physiol 308: F330–F338, 2015. First published December 4, 2014; doi:10.1152/ajprenal.00467.2014.—Chronic lymphocytic leukemia (CLL) is often associated with nephritic syndrome. Effective treatment of CLL by chlorambucil and bendamustine leads to the restoration of renal function. In this contribution, we sought to elucidate the impact of organic anion transporters (OATs) on the uptake of bendamustine and chlorambucil as a probable reason for the superior efficacy of bendamustine over chlorambucil in the treatment of CLL. We examined the effects of structural analogs of p-aminohippurate (PAH), melphalan, chlorambucil, and bendamustine, on OAT1-mediated [3H]PAH uptake and OAT3- and OAT4-mediated [3H]estrone sulfate (ES) uptake in stably transfected human embryonic kidney-293 cells. Melphalan had no significant inhibitory effect on any OAT, whereas chlorambucil reduced OAT1-, OAT3-, and OAT4-mediated uptake of PAH or ES down to 14.6%, 16.3%, and 66.0% of control, respectively. Bendamustine inhibited only OAT3-mediated ES uptake, which was reduced down to 14.3% of control cells, suggesting that it interacts exclusively with OAT3. The IC50 value for OAT3 was calculated to be 0.8 μM. Real-time PCR experiments demonstrated a high expression of OAT3 in lymphoma cell lines as well as primary CLL cells. OAT3-mediated accumulation of bendamustine was associated with reduced cell proliferation and an increased rate of apoptosis. We conclude that the high efficacy of bendamustine in treating CLL might be partly contributed to the expression of OAT3 in lymphoma cells and the high affinity of bendamustine for this transporter.

organic anion transporter; solute carrier family 22; uptake transporter; cytostatics; bendamustine; chlorambucil; chronic lymphocytic leukemia

CHRONIC LYMPHOCYTIC LEUKEMIA (CLL) is the most common form of adult leukemia in the Western countries, accounting for nearly 40% of all leukemia (17). After the diagnosis of CLL, the survival period ranges from months to >10 yr and is often associated with nephritic syndrome (25). Histological examination of renal biopsies from CLL patients showed increased basement membrane thickness induced by interstitial CLL infiltration, causing a diffuse membranous glomerulonephritis (9). A retrospective analysis of clinical data confirmed the pathophysiological link between glomerulonephritis and B cell proliferation. Effective treatment of the malignancy by chlorambucil monotherapy showed, additionally, a chlorambucil-induced complete remission of the glomerulonephritis and substantial improvement of renal function (27).

The introduction of purine analogs almost 30 yr ago, especially of fludarabine, changed the frontline treatment paradigm for CLL. Compared with chlorambucil, fludarabine showed improved response rates and progression-free survival, but the overall survival was not enhanced (31). In parallel, bendamustine was developed with the intention of producing an anticancer agent that combined both alkylating and antimetabolite properties (13). Several studies have documented that bendamustine acts primarily as an alkylating drug, which induces the formation of intrastrand and interstrand cross-links between DNAs (15, 24, 36). In a patient with a B cell lymphoma treated with rituximab and bendamustine, markedly improved renal function was observed (3). In addition, urinary sediment became normal and proteinuria disappeared completely. These findings were in contrast to observations made during chemotherapy with cyclophosphamide, oncovin (vincristine), and prednisone (3).

Recently, bendamustine was compared with chlorambucil in a randomized first-line therapy with 319 previously untreated advanced CLL patients. Bendamustine showed significantly higher overall responses and progression-free survival compared with chlorambucil (20). Based on this vital clinical study, the United States Food and Drug Administration approved bendamustine for CLL treatment in the year 2008. Bendamustine shares similarities with chlorambucil and p-aminohippurate (PAH) with respect to the butyric acid side chain, as shown in Fig. 1. PAH is a well-known model substrate of renal organic anion transporters (OATs). OAT1 and OAT3 are expressed at the basolateral membrane and OAT4 at the apical membrane of proximal tubule cells, respectively, and are involved in the renal excretion of a large number of drugs (1, 5, 33, 37, 42).

In the present study, we examined the interactions of OATs (OAT1, OAT3, and OAT4) with the cytostatic agents melphalan, chlorambucil, and bendamustine. We then determined the expression of OATs in lymphoma cell lines as well as in samples from CLL patients. To evaluate the role of OAT-mediated uptake of cytostatics for cell proliferation, we performed thymidine incorporation assays and measured apoptosis induced by the alkylating drugs. Surprisingly, lymphoma cells express the “renal” transporter OAT3, rendering them sensitive to bendamustine.

MATERIALS AND METHODS

Reagents. Cell culture materials, including FCS, PBS, RPMI-1640, and DMEM-LG, were purchased from Invitrogen (Groningen, The Netherlands). TRizol Reagent was from Invitrogen, and murine leu-

Downloaded from http://ajprenal.physiology.org/ by 10.220.32.246 on June 11, 2017
kocyte virus (MuLV) reverse transcriptase was obtained from Promega (Mannheim, Germany). Chemical reagents (analytical grade) were purchased from Sigma-Aldrich (Munich, Germany). Hygromycin was obtained from AppliChem (Darmstadt, Germany). Real-time TaqMan primers and TaqMan buffer were purchased from Applied Biosystems (Darmstadt, Germany). Previously described B and T lymphoma cell lines (Karpas, SUDHL4, Raji, Hut78, and Jurkat cells) were obtained from a public depository (DSMZ, Braunschweig, Germany).

**Quantitative real-time PCR.** Suspension-cultured B and T lymphoma cell lines and patient samples were used to obtain total RNA using TRIzol Reagent following the manufacturer’s protocol. The concentration and quality of the purified RNA were quantified using a Gene Quant II spectrophotometer (Amersham Bioscience). cDNA was prepared from RNA using MuLV reverse transcriptase as per the protocol of the manufacturer. Briefly, 2 μg of total RNA were reverse transcribed into cDNA in a reaction mixture containing 200 units of MuLV enzyme, 500 μM of each dNTP, and 2.5 μg/μl of random primers in a 20-μl reaction volume for 1 h at 37°C and 10 min at 70°C. Diluted cDNA (5 μl) was used in the real-time PCR mixture containing 12.5 μl of 2× reaction buffer, 1.25 μl of 25× TaqMan-primer mixture, and 6.25 μl of nuclease-free water in a total volume of 25 μl. The mixture was transferred into a 96-well plate and covered with an optical adhesive film. The plate was then transferred to the ABIPrism 7000 real-time PCR cycler (Applied Biosystems). The PCR program consisted of the following steps: 2 min at a 52°C uridine glycosylase step, 10 min at a 96°C TaqMan polymerase activation step, and 40 cycles of 15 s at 96°C and 1 min at 60°C. Fluorescence reading was performed on the last step of each cycle. Data were analyzed by ABIPrism 7000 software.

**Transport measurements.** T-REx human embryonic kidney (HEK)-293 cells stably expressing human OAT1, OAT3, or OAT4 were harvested and plated into 24-well plates (2×10^5 cells/well). After 72 h of incubation, cells were washed three times with mammalian Ringer solution containing 130 mM NaCl, 4 mM KCl, 1 mM CaCl_2, 1 mM MgSO_4, 1 mM NaH_2PO_4, 20 mM HEPES, and 20 mM D-glucose with pH adjusted with 1 M NaOH to 7.4. After a wash, cells were incubated with 200 μl of transport solution containing 1 μM [^3H]PAH or 20 nM [^3H]ES with or without 100 μM of the specific cytostatic in mammalian Ringer solution. After 5 min of incubation at room temperature, cells were washed with ice-cold PBS and lysed with 500 μl of 1 M NaOH solution for 20 min. The lysed mixture was neutralized with 500 μl of 1 M HCl and transferred into scintillation vials. Incorporated radioactivity was counted by adding 2.5 ml Lumasafe scintillation solution (Perkin-Elmer) to each sample in a scintillation counter (TriCarb 1500 Packard, Meriden, CT). To determine the affinity of the transporter for the alkylation drugs, concentration-dependent cis-inhibition experiments were performed. The inhibitory effect of the drugs was calculated using four-parameter Hill equations with SigmaPlot 11.0 (SPSS Science, Chicago, IL) to determine the concentration that causes half-maximal inhibition of the uptake (IC_50, μmol/l) as follows:

\[
I = I_0 + \frac{I_{\text{max}} + c^n}{c^n + IC_{50}^n}
\]

where \(I_0\) is the inhibitory baseline effect (in %), \(I_{\text{max}}\) is the maximal inhibitory effect (in %), \(c\) is the inhibitor concentration (in μmol/l), and \(n\) is the Hill exponent (\(n = 1\)).

**Proliferation assay.** Proliferation was estimated by[^3H]thymidine incorporation as previously described (32, 35). Human OAT1- or human OAT3-expressing HEK-293 cells were harvested and seeded onto 24-well plates at a concentration of 5×10^4 cells/well. After 24 h, cells were incubated with different concentrations of chlorambucil and bendamustine for 30 min and then washed three times with the medium. Cells were then incubated in a medium containing 4 μM[^3H]thymidine for 15 min. After this, cells were fixed with 5% trichloracetic acid for 30 min on ice. Cells were washed twice with ice-cold PBS and once with 96% ethanol. Pellets were then dissolved in 1 M NaOH for 20 min and neutralized with 1 M HCl. Incorporated radioactivity was counted by a scintillation counter (TriCarb 1500 Packard).

**Bendamustine-dependent cytotoxicity.** Flow cytometric analysis of a B lymphoma cell line (Raji) and a T lymphoma cell line (Jurkat) was performed. Cells were washed and resuspended in PBS to a concentration of 2.5×10^6 cells/ml. The cells were then treated with 100 μM bendamustine or simultaneously with bendamustine and 1 mM probenecid. Untreated cells were used as a control. After 15 min of incubation with cytostatics, cells were washed three times with PBS to remove the drugs and grown further for 12 h in culture medium without cytostatics. Cells were stained with annexin V-propidium iodide (PI). During this procedure, cells were pelleted and resuspended in staining buffer [10 mM HEPES-NaOH (pH 7.4), 140 mM NaCl, 5 mM CaCl_2, and PI at a final concentration of 10 μM] containing 20 μl of annexin V-Fluos (Roche Diagnostics, Mannheim, Germany) for each milliliter of buffer and subsequently analyzed on a FACS Calibur. All assays were performed in duplicate in three independent experiments.
We calculated the mean of the total apoptotic events from three independent experiments. Furthermore, we determined benzamidine-induced apoptosis as well as benzamidine plus probenecid-induced apoptosis in both lymphoma cells using a calculation system previously described by Friesen et al. (12). The formula used was 100 × [drug-induced apoptosis (in %) − spontaneous apoptosis in cell medium (in %)]/[100% − spontaneous apoptosis in cell medium (in %)].

RESULTS

Interaction of alkylating cytostatics with OAT1, OAT3, and OAT4. To elucidate the interactions of human OAT1, human OAT3, and human OAT4 with the alkylating cytostatics chlorambucil, melphalan, and bendamustine, we examined the inhibition of human OAT1-mediated \(^{3}H\)PAH uptake and human OAT3- and human OAT4-mediated \(^{3}H\)ES uptake. Transport activity of OAT1, OAT3, or OAT4 was demonstrated in stably transfected HEK-293 cells by measuring the uptake of the radiolabeled model substrates without cytostatic drugs in Ringer buffer compared with nontransfected cells (Fig. 2). Human OAT1-mediated PAH uptake and OAT3 and OAT4 significantly facilitated ES uptake in stably transfected cells with influx rates of 20.2 ± 1.3 pmol·5 min\(^{-1}\)·10\(^{6}\) cells\(^{-1}\) for PAH and 39.3 ± 6.2 and 45.2 ± 4.8 fmol·5 min\(^{-1}\)·10\(^{6}\) cells\(^{-1}\) for ES, respectively. Untransfected cells showed uptake of 0.89 ± 0.13 pmol·5 min\(^{-1}\)·10\(^{6}\) cells\(^{-1}\) for PAH and 4.6 ± 0.86 and 3.9 ± 0.6 fmol·5 min\(^{-1}\)·10\(^{6}\) cells\(^{-1}\) for ES, respectively. To test for potential interactions of the alkylating cytostatic drugs with OATs, 100 μM of each drug were added as a competitor to PAH or ES into the assay. The inhibitory effects of these drugs on OAT1-, OAT3-, or OAT4-mediated uptake of PAH or ES are represented as percentages of uptake in the absence of these drugs (Fig. 3). OAT1-mediated PAH uptake was inhibited down to 90.4 ± 5.7%, 80.9 ± 7.2%, and 14.6 ± 0.8% of control by melphalan, benzamidine, and chlorambucil, respectively (Fig. 3A). Human OAT3 transport activity was reduced down to 16.3 ± 1.3% by chlorambucil and 14.3 ± 2.7% by benzamidine. Melphalan stimulated the uptake of ES by human OAT3 to 124.0 ± 3.8% (Fig. 3B). Chlorambucil was the only alkylating cytostatic drug that inhibited human OAT4-facilitated ES uptake to 66.0 ± 4.0% (P < 0.001). Bendamustine did not show any interaction with human OAT4. On the other hand, melphalan significantly stimulated human OAT4-mediated ES uptake (P < 0.001) by 86.4% (Fig. 3C).

Concentration-dependent inhibition of OAT1- and OAT3-mediated uptake. Next, we determined the affinity of OAT1 and OAT3 for chlorambucil as well as the affinity of OAT3 for benzamidine by performing concentration-dependent inhibition experiments. Figure 4 shows the inhibitory effects of the alkylating drugs in percentages of untreated samples. Calculated IC\(_{50}\) values of OAT1 and OAT3 for chlorambucil were 44.3 ± 2.6 and 9.5 ± 1.9 μM, respectively. For bendamustine, the IC\(_{50}\) value was 0.8 ± 0.1 μM.

Determination of cell proliferation. To elucidate whether cells expressing OAT1 and OAT3 exhibit an inhibition of proliferation upon treatment with alkylating drugs, we performed \(^{3}H\)thymidine incorporation assays. Treatment of OAT3-transfected HEK-293 cells with increasing concentrations of chlorambucil induced a 20–25% decrease in thymidine incorporation similar to mock-transfected cells (Fig. 5A). However, OAT1-expressing cells demonstrated significantly higher reductions of thymidine incorporation compared with untreated or mock cells (Fig. 5A), suggesting that enhanced OAT1-mediated uptake of chlorambucil caused the increased inhibition of cell proliferation. Similarly, OAT3-expressing cells showed decreased proliferation in the presence of bendamustine (Fig. 5B); in contrast, chlorambucil and bendamustine were ineffective in mock-transfected cells (Fig. 5, A and B).

Expression of OAT3 in lymphoma cell lines and CLL patients. We examined the expression of OAT1, OAT2, OAT3, and OAT4 in six lymphoma cell lines (Karpas422, Raji, SudHL4, L428, Jurkat, and Hut78) by quantitative RT-PCR. Human OAT1, OAT2, and OAT4 were not expressed in any of the lymphoma cell lines tested. We discovered, however, high expression levels of human OAT3 in all lymphoma cell lines tested (Fig. 6A). Lowest expression was observed in Karpas422 and Raji cells at 6- to 8-fold higher DC\(_{50}\) levels (where DC\(_{50}\) is threshold cycle) than in normal lymphocytes, whereas all other

![Fig. 2. Organic anion transporter (OAT)-mediated uptake of radiolabeled organic anions. Stable expression of human hOAT1, hOAT3, and hOAT4 was verified by measuring the uptake of 1.0 μM \(^{3}H\)PAH (OAT1) or of 20 nM \(^{3}H\)estrone sulfate (ES) (OAT3 and OAT4) (hatched columns). Solid columns represent the uptake of PAH and ES in vector-transfected mock human embryonic kidney (HEK)-293 cells. Values are means ± SE of three independent (n = 3) experiments with three repeats each.](http://ajprenal.physiology.org/content/doi/10.1152/ajprenal.00467.2014/fig)
cell lines showed 13- to 14-fold higher ΔCt levels of OAT3 expression compared with control lymphocytes (Fig. 6A). As OAT3 was highly expressed in lymphoma cell lines, we examined its expression in four samples of CLL patients. Expression of OAT3 in the four samples of patients showed 5- to 9-fold higher levels of OAT3 mRNA expression compared with control lymphocytes (Fig. 6B).

**Bendamustine-induced and OAT3-mediated specific apoptotic effects in lymphoma cells.** To examine OAT3-mediated, bendamustine-induced cytotoxicity in lymphoma cell lines, we selected Raji cells as a low-OAT3 expression system and Jurkat cells as a high-OAT3 expression system and then quantified apoptotic cell death by annexin V and PI staining. We incubated lymphoma cells with and without either bendamustine alone or bendamustine in combination with probenecid, an OAT3 inhibitor. After removal of the cytostatic drugs, cells were subsequently grown for 12 h, and apoptotic events were quantified by FACS analysis [Fig. 7A (a representative experiment)]. Treatment with bendamustine increased apoptotic events in both cell lines by threefold compared with low-level spontaneous apoptosis in untreated control cells. The simultaneous incubation of bendamustine with probenecid reduced the proportions of apoptotic cells significantly by 31–38% (Fig. 7B). Bendamustine-induced specific apoptosis for Raji and Jurkat cells was 6.0 ± 0.18% and 11.3 ± 0.4%, respectively, as calculated with the equation previously described by Friesen et al. (12). Simultaneous incubation with probenecid reduced bendamustine-induced specific apoptosis to 3.3 ± 0.8% and 5.2 ± 0.3% for Raji and Jurkat cells, respectively (Fig. 7C). These results demonstrate, for the first time, the impact of OAT3 on the cytostatic efficacy of bendamustine in lymphoma cells.

**DISCUSSION**

Renal syndromes caused by leukemic infiltration of the kidneys in CLL have been reported in several cases, and retrospective as well as autopsy studies have indicated a broad spectrum of nephropathy, including, e.g., membranoproliferative glomerulonephritis, mesangioproliferative glomerulonephritis, and tubular necrosis (9, 18, 25, 30). Treatment of CLL patients with severe kidney diseases by alkylating drugs like chlorambucil and bendamustine led to a significant improvement of renal function (3, 27).

Chlorambucil, bendamustine, and melphalan are antineoplastic agents containing an alkylating nitrogen mustard group. In lymphoid malignancies such as CLL, these drugs serve in efficient mono frontline therapy as well as in combination with other antineoplastic agents, e.g., fludarabine (11). Among other factors, the efficacy of chemotherapy depends on the intracellular drug concentration, which, in turn, is determined by an equilibrium of drug uptake into and drug release from tumor cells. Whereas drug release driven by ATP-dependent ABC transporters has been studied in detail in the past, relatively little is known on how antineoplastic agents are taken up into tumor cells. In this contribution, we

Fig. 3. Cis-inhibition of OAT-mediated PAH or ES uptake by alkylating drugs. The inhibition experiment was performed using 100 μM of either melphalan, chlorambucil, or bendamustine competing with hOAT1-mediated uptake of 1.0 μM [3H]PAH (A) or OAT3- and OAT4-mediated uptake of 20 nM [3H]ES (B and C) (hatched columns). Solid columns represent inhibition of the respective uptake in mock cells. All experiments were standardized by setting uptake in control (Ringer solution without inhibitor) of each experiment to 100%. Values are means ± SE of three independent (n = 3) experiments with three repeats each. *Significant inhibition of OAT-mediated substrate uptake by alkylating drugs (***P < 0.001); ns, no significant inhibition.

AJP-Renal Physiol • doi:10.1152/ajprenal.00467.2014 • www.ajprenal.org
considered renal OATs (OAT1, OAT3, and OAT4) as possible pathways for drug uptake for two reasons. First, OATs are known for their very broad substrate specificity, i.e., they can transport drugs of various chemical structures into cells. Second, melphalan, chlorambucil, and bendamustine share structural similarities with PAH, a model organic anion used to study renal plasma flow mediated by OAT function.

The alkylating agent melphalan carries a negatively charged carboxyl group and a positively charged amino group, resembling an amino acid. A previous study (26) demonstrated leucine-sensitive uptake of melphalan into murine leukemia cells, suggesting the involvement of an amino acid transporter.
twofold change (2CT,c) was correlated to that of the lymphoma cell lines (H9004).

After standardization, OAT3 expression of control lymphocytes of healthy results are shown as expressed in Xenopus laevis.

Indeed, L-type amino acid transporter 1 (LAT1; SLC7A5), means/H11006 chronic lymphatic leukemia (CLL) patients (B) was used to perform quantification of OAT3 mRNA expression in lymphoma cells. Total RNA extracted from six lymphoma cell lines (A) and peripheral blood from control Karpas Raji SudHL4 L428 Jurkat Hut78. Data are means ± SE of three (A) and two (B) independent experiments with two repeats each.

Fig. 6. Quantification of OAT3 mRNA expression in lymphoma cells. Total RNA extracted from six lymphoma cell lines (A) and peripheral blood from chronic lymphatic leukemia (CLL) patients (B) was used to perform quantitative expression analysis by TaqMan real-time PCR. The cDNA quantity of each cell preparation was normalized using the GAPDH threshold cycle (Ct). After standardization, OAT3 expression of control lymphocytes of healthy donors (ΔCt,c) was correlated to that of the lymphoma cell lines (ΔCt,L). The results are shown as ΔCt (ΔCt,c/ΔCt,L). Each cycle difference represents a twofold change (2ΔCt) in the relative mRNA expression level. Therefore, larger columns indicate higher expression in lymphoma cells compared with control lymphocytes. Control lymphocytes are set to unity (ΔCt,c). Data are means ± SE of three (A) and two (B) independent experiments with two repeats each.

Bendamustine mainly functions as an alkylating agent caus- ing the formation of intrastrand and interstrand cross-links between the bases of DNA that, in turn, inhibit DNA replication and transcription (13). In preclinical studies, bendamustine acted on tumor cells otherwise resistant to alkylating or intercalating drugs, suggesting, among other reasons, a higher accumulation inside cells (16, 36). Several clinical studies with bendamustine have documented a higher overall response in...
patients with non-Hodgkin’s lymphoma, multiple myeloma, and relapsed or refractory chronic lymphatic leukemia compared with chlorambucil (4, 19, 34). A comparison between chlorambucil and bendamustine in a phase III multicenter randomized study on 319 patients revealed a higher complete response, progression-free survival, and higher duration of remissions in bendamustine-treated patients (21). The molecular basis for the better outcomes in bendamustine-treated patients was hitherto unknown.

Bendamustine is extensively metabolized in the liver by oxidation, carboxylic acid formation, N-dealkylation, sulfation, as well as conjugation with cysteine and glutathione, leading to 7–25 different metabolites (8, 10, 38, 39). The metabolites and 30–50% of the parental drug are excreted into the bile and urine. Although the exact contribution of both pathways is controversial, reported data suggest that renal excretion of bendamustine amounts to 45% of the overall elimination (13) and is higher for the parental compound than for metabolites (29). The kidneys could, therefore, be equipped with transporters for bendamustine excretion.

Here, we tested a possible interaction of the anionic bendamustine with OAT1, OAT3, and OAT4, transporters involved in the renal excretion of a variety of anionic drugs (6, 41). OAT1 and OAT4 were slightly or not at all inhibited in the

---

**Fig. 7. Bendamustine-induced apoptosis in lymphoma cells.**

A: representative experiment of scattergrams of untreated and bendamustine or bendamustine plus probenecid treated lymphoma cells stained with annexin V antibodies and propidium iodide (PI). B: spontaneous apoptosis and apoptotic events resulting after 15 min of incubation with bendamustine alone or together with probenecid. Values are means ± SE of three independent experiments with each duplicate. C: bendamustine-induced specific apoptosis (in %) calculated from the whole gated cell number and spontaneous apoptotic events as previously published (12).

§§Significantly induced apoptosis by bendamustine and **significant inhibition of bendamustine-induced apoptosis by probenecid (P < 0.01).
presence of 100 μM bendamustine, suggesting that both trans-
porters hardly interact with this drug. In contrast, OAT3-
mediated ES uptake was nearly abolished by bendamustine.
The IC50 value was 0.8 μM, indicating a very high affinity of
OAT3 for bendamustine. At a dose of 30 to 200 mg/m2 surface
area, peak plasma concentrations of bendamustine between 0.1
and 30 μg/ml were reported (7, 13). These values translate into
concentrations between 0.2 and 8.3 μM (molecular mass: 357.8 g/mol), being in the range of the affinity of OAT3 for
bendamustine. Hence, OAT3 could well be involved in renal
bendamustine excretion.

A more intriguing question was whether OAT3-expressing
cells are more sensitive to the cytostatic actions of bendamus-
tine compared with nonexpressing cells. As tested by thymi-
dine incorporation, OAT3-expressing HEK-293 cells showed
clearly decreased proliferation compared with mock cells with-
out OAT3. This finding strongly suggests that OAT3 is able
to transport bendamustine into cells, leading to a higher intracel-
lar concentration and efficacy of this antineoplastic drug.
OAT3-expressing tumor cells should, therefore, be more sen-
sitive to bendamustine treatment than cells not expressing
OAT3.

We examined six established lymphoma cell lines and cells
from four CLL patients for a possible expression of OAT3.
Surprisingly, lymphoma cell lines and CLL patient cells, but
not lymphocytes from a healthy donor, expressed mRNA for
OAT3, as indicated by a 6- to 12-cycle difference in quantitative
RT-PCR. Each cycle difference represents a twofold change (2^ΔCt) in the relative mRNA expression level.

A 15-min treatment of Raji and Jurkat lymphoma cells with bendamustine and subsequent cultivation for 12 h resulted in a
higher rate of apoptosis, as shown by FACS analysis. Consid-
ering total gated events and spontaneous apoptosis in a calcula-
tion previously described by Friesen et al. (12), bendamus-
tine-induced specific apoptosis was 1.8- and 2.1-fold higher for
Raji and Jurkat cells, respectively, compared with spontaneous
apoptosis. Importantly, the OAT3 inhibitor probenecid reduced bendamustine-induced apoptosis significantly. Therefore, we
conclude that the increase in apoptosis is due to the uptake of
bendamustine by OAT3. Similarly, OAT3 might be responsible
for the bendamustine-induced remission of a B cell CLL-
associated membranoproliferative glomerulonephritis, as it
would increase the cytotoxicity of bendamustine to CLL that
infiltrated the kidney. However, we do not have a direct proof
of this fact.

One of the basic problems of current chemotherapy is the poor
accumulation of the antineoplastic agents within tumor
cells. The application of cytostatic drugs taken up by trans-
porters expressed in the individual tumor may help to amelio-
rate or even to overcome chemoresistance. The present study
shows, for the first time, that OAT1 and OAT3 possess affinity
for the anionic antineoplastic agents chlorambucil and bendamus-
tine. OAT3 has an exceptionally high affinity for bendamus-
tine and appears to transport this agent, because upon

OAT3-expressing model cells showed reduced prolif-
eration. Since OAT3 is expressed in lymphoma cells, the
superior efficacy of bendamustine in treating CLL patients
could now be partially explained by bendamustine uptake into
tumor cells. From the results of the present study, it is evident
that these transporters play a crucial role in the determination
of cytotoxicity of chlorambucil and bendamustine; whether
they play a direct role in the alleviation of CLL-induced nephropathy remains to be elucidated.

ACKNOWLEDGMENTS
The authors thank Sören Petzke for his skillful and excellent technical assistance.

GRANTS
This work was supported by Deutsche José Carreras Leukämie Stiftung Project Grant DJCLS R 06/30v.

DISCLOSURES
No conflicts of interest, financial or otherwise, are declared by the author(s).
No conflict of interest exists. Y. Hagos is a professor at the Institute for
Vegetative Physiology and Pathophysiology of the University Goettingen and
also the CEO and shareholder of PortaCellTec Biosciences GmbH.

AUTHOR CONTRIBUTIONS
Author contributions: Y.H., G.W., and G.B. conception and design of research;
Y.H., P.H., and V.S. analyzed data; Y.H., P.H., V.S., and G.B. interpreted
results of experiments; Y.H. prepared figures; Y.H. and V.V.V.R.M. drafted
manuscript; Y.H., P.H., V.S., V.V.V.R.M., G.W., and G.B. edited and revised
manuscript; Y.H., P.H., V.S., V.V.V.R.M., G.W., and G.B. approved final version
of manuscript; P.H. and V.S. performed experiments.

REFERENCES
1. Anzai N, Kanai Y, Endou H. Organic anion transporter family: current
2. Barnoun K, Leier I, Jeddatschky G, Pourtier-Manzanedo A, Konig J,
Lehmann WD, Keppeler D. Multidrug resistance protein-mediated trans-
port of chlorambucil and melphanal conjugated to glutathione. Br J Cancer
3. Bartel C, Obermuller N, Rummel MJ, Geiger H, Hauser IA. Remis-
sion of a B cell CLL-associated membranoproliferative glomerulonephri-
2008.
4. Bergmann MA, Goebeler ME, Herold M, Emmerich B, Wilhelm M,
Ruefels C, Boening L, Hallek MJ. Efficacy of bendamustine in patients
with relapsed or refractory chronic lymphocytic leukemia: results of a
phase VII study of the German CLL Study Group. Haematologica 90:
1357–1364, 2005.
5. Bureckhardt BC, Bureckhardt G. Transport of organic anions across the
basolateral membrane of proximal tubule cells. Rev Physiol Biochem
6. Bureckhardt G, Bureckhardt BC. In vitro and in vivo evidence of the
importance of organic anion transporters (OATs) in drug therapy. Handb
8. Chovan JP, Li F, Yu E, Ring SC. Metabolic profile of [14C]bendamus-
tine in rat urine and bile: preliminary structural identification of metabo-
9. Da’as N, Polliack A, Cohen Y, Amir G, Darmon D, Kleinman Y,
Goldfarb AW, Ben-Yehuda D. Kidney involvement and renal manifes-
tations in non-Hodgkin’s lymphoma and lymphocytic leukemia: a retro-
10. Dubbelman AC, Jansen RS, Rosing H, Darwish M, Hellriegel E,
Robertson P Jr, Schellens JH, Beijnen JH. Metabolic profiling of bendamus-
tine in urine of cancer patients after administration of [14C]-bendamus-
11. Foon KA, Hallek MJ. Changing paradigms in the treatment of chronic
12. Friesen C, Herr I, Krammer PH, Debatin KM. Involvement of the
CD95 (APO-1/FAS) receptor/ligand system in drug-induced apoptosis in
Human organic cation transporter 1 is expressed in lymphoma cells and
increases susceptibility to irinotecan and Paclitaxel. J Pharmacol Exp Ther

AJP-Renal Physiol • doi:10.1152/ajprenal.00467.2014 • www.ajprenal.org


24. Lieber S, Rennig L. F338 IMPACT OF OAT3 ON BENDAMUSTINE UPTAKE


38. Yanagida O, Yanagida O, Chairoungdua A, Kim DK, Sekawa H, Nii T, Wright SH, Dantzler WH.