Human Vascular Smooth Muscle Cells Express a Urate Transporter

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An elevated serum uric acid is associated with the development of hypertension and renal disease. Renal regulation of urate excretion is largely controlled by URAT1 (SLC22A12), a member of the organic anion transporter superfamily. This study reports the specific expression of URAT1 on human aortic vascular smooth muscle cells, as assessed by reverse transcription–PCR and Western blot analysis. Expression of URAT1 was localized to the cell membrane. Evidence that the URAT1 transporter was functional was provided by the finding that uptake of [14C]-urate was significantly inhibited in the presence of probenecid, an organic anion transporter inhibitor. It is proposed that URAT1 may provide a mechanism by which uric acid enters the human vascular smooth muscle cell, a finding that may be relevant to the role of uric acid in cardiovascular disease.

Methods and Materials

Cell Culture

Human aortic VSMC were obtained from Prof. Elaine Raines (University of Washington, Seattle, WA) and cultured as described previously (22). Briefly, cells were cultured in DMEM (Invitrogen, Carlsbad, CA) supplemented with 20% FBS (Invitrogen), 25 mM HEPES (Invitrogen), 100 U/ml penicillin, and 100 mg/ml streptomycin (Invitrogen). Cells were subcultured 1:3 on confluence. All experiments were performed on at least three independent occasions with cells between passages 4 and 8.

Uric Acid Stimulation

Cells were grown to 70% confluence, serum-starved 24 h before experimentation and challenged with varying concentrations of uric acid (3 to 12 mg/dl) for 6 h to collect RNA and 24 h to collect protein. In addition, RNA and protein were collected from nonstimulated cells at the same time points for comparison.

Reverse Transcription–PCR Amplification

RNA was isolated using Tri-Reagent (Sigma, St. Louis, MO) and extracted with isopropanol (Sigma) followed by ethanol precipitation. One microgram of RNA was used to create cDNA, according to providers’ instructions (Bio-Rad Laboratories, Hercules, CA). Two micro-
liters of cDNA product was used in a 50-μl final volume reaction that contained 1.5 mM MgCl₂, 200 μl dNTP, iTaq buffer (200 mM Tris-HCl [pH 8.4] and 500 mM KCl), 100 nM of both sense and antisense primers, and 1.25 U of iTaq DNA polymerase (Bio-Rad Laboratories). cDNA preparations from human kidney, human liver, and human placenta poly A⁺ RNA (Clontech, San Jose, CA) were used as positive controls for the appropriate gene: human kidney for OAT1, OAT3, and URAT1 (15,17,19); human liver for OAT2 (16); and human placenta for OAT4 (18). A negative control that consisted of the PCR mixture excluding template cDNA was included. The PCR primers and conditions used are shown in Table 1. Results shown are representative agarose gels of at least three independent experiments. In addition, the identity of the PCR products produced was confirmed by forward and reverse sequence analysis (Sigma Genosys, The Woodlands, TX).

**Western Blot Analysis for URAT1**

Cells were lysed in RIPA buffer (150 mM NaCl, 1% Nonidet P-40, 0.5% sodium deoxycholate, 0.1% SDS, and 50 mM Tris buffer [pH 8.0]), and Western blotting was performed using 15 μg of protein as described previously (23). Briefly, after electrophoresis and transfer by electrophoretic transfer, membranes were blocked in 5% nonfat milk for 1 h before incubation with rabbit anti-human URAT1 (1:500; Alpha Diagnostic Inc., San Antonio, TX) overnight at 4°C. Appropriate horseradish peroxidase antibodies (Dako, Carpinteria, CA) were then used, and bands were detected by chemiluminescence (Amersham Biosciences, Piscataway, NJ). Blots were stripped and reprobed with human glyceraldehyde-3-phosphate dehydrogenase (1:300; Chemicon International, Temecula, CA), to assess equal loading. The result of the Western blot shown is representative of at least three independent experiments.

**Total Membrane Isolation**

Human VSMC that were grown to 70% confluence were washed three times with ice-cold Krebs Ringer Buffer (128 mM NaCl, 4.7 mM KCl, 1.25 mM MgSO₄·7H₂O, 1.25 mM CaCl₂·2H₂O, and 5 mM phosphate salts), collected in Buffer A (20 mM Tris-HCl, 1 mM EDTA, and 255 mM sucrose [pH 7.4]) that contained protease inhibitors, homogenized on ice, and centrifuged at 55,000 rpm for 70 min at 4°C. The cell pellet was resuspended in 200 μl of Buffer A, and the protein concentration was determined human aortic VSMC (Figure 1). No detectable expression of OAT1 (573 bp), OAT2 (530 bp), OAT3 (902 bp), or OAT4 (434 bp) mRNA was demonstrated in nonstimulated or uric acid–stimulated human aortic VSMC (Figure 1). No detectable expression of OAT1 (573 bp), OAT2 (530 bp), OAT3 (902 bp), or OAT4 (434 bp) mRNA was demonstrated in nonstimulated or uric acid–stimulated human aortic VSMC. Nevertheless, expression of OAT1 and OAT3 was present in human kidney, whereas OAT2 and OAT4 were expressed in human liver and placenta, respectively, consistent with their known sites of expression (15–19) (Figure 1). A band consistent with URAT1 mRNA was observed in both nonstimulated and uric acid–stimulated human VSMC and also in human kidney (365 bp; Figure 1). Forward and reverse

**Urate Uptake by VSMC**

VSMC (1 × 10⁶) were incubated with 50 μM ¹⁴C-urate (American Radiolabeled Chemicals, St. Louis, MO) in Hanks medium (Invitrogen) supplemented with 1 mM t-glutamine (Invitrogen) and 100 μM sodium pyruvate (Invitrogen) for 0, 5, 15, 30, and 60 min at 37°C in a 5% CO₂ incubator. To stop the reaction, we removed the incubation medium and washed the cells three times with ice-cold Hanks medium. The cells were lysed with 0.1 N sodium hydroxide (Sigma) for 20 min, collected into 4-ml scintillation fluid (Fisher Scientific, Pittsburgh, PA) and measured in a β counter (Beckman Coulter Inc., Fullerton, CA). For determination of the specificity of urate uptake, the OAT inhibitor probenecid (1 mM; Sigma) was added to the reaction for the same time course, and samples were collected and measured as described above. All uptake experiments were performed on three separate occasions, and an average value was taken. Data were assessed using a one-way ANOVA with Bonferroni analysis.

**Results**

First, we examined the mRNA expression of OAT1, OAT2, OAT3, OAT4, and URAT1 in nonstimulated or uric acid–stimulated human aortic VSMC (Figure 1). No detectable expression of OAT1 (573 bp), OAT2 (530 bp), OAT3 (902 bp), or OAT4 (434 bp) mRNA was demonstrated in nonstimulated or uric acid–stimulated VSMC. Nevertheless, expression of OAT1 and OAT3 was present in human kidney, whereas OAT2 and OAT4 were expressed in human liver and placenta, respectively, consistent with their known sites of expression (15–19) (Figure 1). A band consistent with URAT1 mRNA was observed in both nonstimulated and uric acid–stimulated human VSMC and also in human kidney (365 bp; Figure 1). Forward and reverse

Table 1. Primer sequences for the human organic anion transporters

<table>
<thead>
<tr>
<th>Gene</th>
<th>Sequence</th>
<th>Corresponding Nucleotides</th>
<th>Annealing Temperature</th>
<th>Number of Cycles</th>
<th>Amplicon Size</th>
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<tr>
<td>hOAT1</td>
<td>Forward: CCA CCT CTT CCT CTG CCT CTC CAT Reverse: GTC TGT TTC CCT TGC CTC TGC TCC</td>
<td>1266 to 1289</td>
<td>60°C</td>
<td>25</td>
<td>573 bp</td>
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<tr>
<td>hOAT2</td>
<td>Forward: CTA TCC CCA GGC TCT CCC CAA CAC Reverse: GAA GCC ATC GCC AGT CCC GTC TCA</td>
<td>1838 to 1815</td>
<td>62°C</td>
<td>25</td>
<td>530 bp</td>
</tr>
<tr>
<td>hOAT3</td>
<td>Forward: GCT CTT CCT CCT ATC ATC CTG GTG Reverse: CTG GCT CCT GCT TTT GCT TCT TTG</td>
<td>252 to 275</td>
<td>62°C</td>
<td>25</td>
<td>530 bp</td>
</tr>
<tr>
<td>hOAT4</td>
<td>Forward: TGC CCT CTT GAG TTT CCT T</td>
<td>781 to 758</td>
<td>60°C</td>
<td>20</td>
<td>902 bp</td>
</tr>
<tr>
<td>hURAT1</td>
<td>Forward: TTG ATT GCC AGG AGG TCAA CC Reverse: GGT TAA GTG GAG TGC TCG GTC AG</td>
<td>1642 to 1619</td>
<td>740 to 761</td>
<td>60°C</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2355 to 2374</td>
<td>35</td>
<td>365 bp</td>
<td></td>
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sequencing showed that the PCR products had >99.0% homology with the expected human URAT1 gene sequence (data not shown).

URAT1 protein also was detected in the human VSMC by Western blotting (Figure 2A, top). A band of 40 kD was detected in the nonstimulated and uric acid–stimulated cells. Equality of loading was confirmed by comparative glyceraldehyde-3-phosphate dehydrogenase expression (Figure 2A, bottom).

URAT1 is expressed on the apical membrane of epithelial cells of the human proximal tubule (19). We therefore examined whether URAT1 was expressed on the membrane of human VSMC by Western blot analysis and immunocytochemistry. As can be seen from the representative blot (Figure 2B), URAT1 was expressed on the nonstimulated and uric acid–stimulated (6 h) human aortic VSMC, as assessed by RT-PCR. The results shown are representative of at least three independent experiments. The specificity of the URAT1 observations was also confirmed by both forward and reverse sequencing.

Next, we examined uric acid transport in human VSMC. As shown in Figure 4, uptake of radiolabeled urate increased in VSMC over time, with the highest level being achieved after 60 min. It has been shown that several OAT inhibitors, such as probenecid (19), inhibit the transport of uric acid via URAT1. Consistent with this observation, probenecid blocked urate uptake (Figure 4) at all time points, significantly at both 30 and 60 min.

**Discussion**

We examined the expression of various OAT in human VSMC. mRNA expression of OAT1, OAT2, OAT3, and OAT4 was not detected in nonstimulated or uric acid–stimulated human aortic VSMC. In contrast, URAT1 mRNA and protein were expressed by both nonstimulated and uric acid–stimulated human VSMC. Consistent with URAT1 being a transporter, we demonstrated the presence of URAT1 on the membrane of these cells. We further showed the presence of a functional OAT in human aortic VSMC, because the cells actively took up urate over a 60-min time course and the uptake was reduced by probenecid. These studies are consistent with previous studies in Xenopus oocytes that express URAT1 (19), in which uptake of urate also was significantly inhibited by probenecid.
counts per minute (\( {/H11006} \)) on three separate occasions, and the data are displayed as mean and 60 min with probenecid). The experiments were performed that drugs such as probenecid also may have direct effects on largely has been assumed that these agents are acting solely to relating hyperuricemia to mutations in URAT1.

Urate and accumulation of urate crystals in kidney tubules, a functional URAT1 transporter results in lower levels of blood species that occurs in muscle during exercise (25,26). The lack of gered by the increased production of urate and reactive oxygen trig-ern associated with exercise-induced acute renal failure, trig-

The clinical importance of URAT1 is demonstrated by recent studies showing that mutations in the human gene cause idio-

The clinical importance of URAT1 is demonstrated by recent studies showing that mutations in the human gene cause idiopathic renal hypouricemia (25,26). This rare disorder occurs with a prevalence of 0.12% in most populations, with a higher frequency in Japanese (27,28) and Iraqi-Jews (24). The disorder is characterized by exercise-induced acute renal failure, triggered by the increased production of urate and reactive oxygen species that occurs in muscle during exercise (25,26). The lack of a functional URAT1 transporter results in lower levels of blood urate and accumulation of urate crystals in kidney tubules, leading to necrosis. Currently, there are no published studies relating hyperuricemia to mutations in URAT1.

Uricosuric agents such as probenecid and benzbromarone are commonly used to treat hyperuricemia in patients with gout. It largely has been assumed that these agents are acting solely to inhibit urate reabsorption in the proximal tubule. The observation that URAT1 also is expressed on human VSMC suggests that drugs such as probenecid also may have direct effects on vascular cells. Further studies are planned to determine the role of VSMC expression of URAT1 in normal individuals and patients with cardiovascular disease.

There are several caveats that need to be considered when interpreting the results of this study. First, although we performed forward and reverse sequencing on the PCR products that were obtained from nonstimulated and uric acid–stimulated cells, it would have been optimal to clone and sequence the entire cDNA of URAT1. Second, it would be interesting to explore whether uric acid stimulation alters the expression of URAT1. Although our data suggest that uric acid does not change URAT1 expression, the methods used are nonquantitative. Therefore, further studies need to be performed using techniques such as real-time PCR or Northern analysis. Finally, the data obtained with radiolabeled urate and the addition of probenecid are suggestive of a functional uric acid transporter in human VSMC. However, it should be noted that the concentration of probenecid used may be too low to block urate uptake completely. In addition, other inhibitors such as benzbromarone may be more specific for URAT1 (29). Indeed, to prove definitively that URAT1 is a functional transporter, experiments with antisense constructs or small interfering RNA need to be performed.

**References**


29. Iwanaga T, Kobayashi D, Hirayama M, Maeda T, Tamai I: Involvement of uric acid transporter in increased renal clearance of the xanthine oxidase inhibitor oxypurinol induced by a uricosuric agent, benz bromarone. *Drug Metab Dispos* 33: 1791–1795, 2005